الجامعة الأردنيــــة
كلية الدراسات العليا

التاريـــخ: / /

نموذج رقم (١٦)
اقرار والتزام بالمعايير الأخلاقية والأمانة العلمية وقوانين الجامعة الأردنية وأنظمتها وتعليماتها لطلبة الدكتوراة

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عنوان الأطروحة: Seismotectonics and Seismic hazard in the Gulf of Aqaba region

أعلن بأنني قد التزمت بقوانين الجامعة الأردنية وأنظمتها وتعليماتها وقراراتها السارية المفعول المتعلقة بإعداد أطروحات الدكتوراه عندما قمت شخصيا" بإعداد أطروحتي وذلك بما ينسجم مع الأمانة العلمية وكافة المعايير الأخلاقية المتعارف عليها في كتابة الأطروحات العلمية. كما أنني أعلن بأن أطروحتي هذه غير منقولة أو مستلة من أطاريح أو كتب أو أبحاث أو أي منشورات علمية تم نشرها أو تخزينها في أي وسيلة إعلامية، وتأسيسا" على ما تقدم فإنني أتحمل المسؤولية بأنواعها كافة فيما لو تبين غير ذلك بما فيه حق مجلس العمداء في الجامعة الأردنية بإلغاء قرار منحي الدرجة العلمية التي حصلت عليها وسحب شهادة التخرج مني بعد صدورها دون أن يكون لي أي حق في التظلم أو الاعتراض أو الطعن بأي صورة كانت في القرار الصادر عن مجلس العمداء بهذا الصدد.

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SEISMOTECTONICS AND SEISMIC HAZARD IN THE GULF OF AQABA REGION

By
Asma'a Mohammad Ghannam

Supervisor
Dr. Najib Abou Karaki, Prof

This Dissertation was Submitted in Partial Fulfillment of the Requirements for the Doctor of Philosophy Degree in Geology

Faculty of Graduate Studies
The University of Jordan

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COMMITTEE DESCISION

This Dissertation (Seismotectonics and seismic hazard in the Gulf of Aqaba region) was successfully defined and approved on 5/4/2011.

EXAMINATION COMMITTEE	SIGNATURE
Dr. Najib Abou Karaki, (Supervisor) Prof. of Geophysics/ Seismology, University of Jordan	…………………
Dr. Elias Salameh, (Member) Prof. of Hydrogeology and Hydrochemistry, University of Jordan	…………………
Dr. Ghazi Saffarini, (Member) Prof. of Economic Geology, University of Jordan	…………………
Dr. Abdallah Malkawi, (Member) Prof. of Geotechnical and Dam Engineering, German-Jordanian University	…………………
Dr. Mahmoud Al-Qaryouti, (Member) Dr. of Seismology, Natural Resources Authority	…………………

DEDICATION

TO MY FATHER, MOTHER, SISTER AND BROTHER.

TO EVERY PERSON WHO SUPPORTED AND ADVICED ME DURING THE PRIGRESS OF THIS WORK

ACKNOWLEDGEMENT

All glory to Allah who made this small objective a reality, and gave me the ability to complete my research. I wish to extend my gratitude to everyone who made this work possible.

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LIST OF ABBREVIATIONS

RRF	Ridge-Ridge-Fault
RRR	Ridge-Ridge-Ridge
DST	Dead Sea Transform
JSO	Jordan Seismological Observatory
IPRG	Institute for Petroleum Research and Geophysics
ISS	(The British) International Seismological Summary
ISC	International Seismological Center
UNJ	University of Jordan seismological station
NEIS	National Earthquake Information Service
NRA	Natural Resources Authority
NRIAG	National Research Institute of Astronomy and Geophysics
SNSN	Saudi National Seismic Network
ASE	Apparent Station Efficiency
PSE	Practical Station Efficiency
O.T	Origin Time
RMS	Root Mean Square
EMSC	European-Mediterranean Seismological Centre
PGA	Peak Ground Acceleration
ABK	N..Abou-Karaki (1987)
AMB	N. Ambraseys and M. Barazangi (1989)
BEM	A. Ben-Menahem (1979)
ETA	E. Al-Tarazi (1992)
HAS	N. Hasweh (1986)

SEISMOTECTONICS AND SEISMIC HAZARD IN THE GULF OF AQABA REGION

By
Asma Mohammad Taher Ghannam

Supervisor
Dr. Najib Abou Karaki, Prof

ABSTRACT

Earthquakes in the Gulf of Aqaba were compiled from Jordan Seismological Observatory (JSO) bulletins, Saudi Arabia (SNSN, King Abdulaziz City for Sci. and Tech) and Egypt, National Research Institute of Astronomy and Geophysics (NRIAG) Helwan sources and were relocated after reexamining the P and S arrival times, testing the efficiency of stations used to determine the location of Aqaba events, calculating the average value of Vp/ Vs, and choosing the best crustal model for the study area. The earthquake epicenters are distributed along the eastern side of the Gulf of Aqaba.

The development of a seismic hazard map of the Gulf of Aqaba was based on probabilistic seismic hazard assessment using historical and instrumental earthquakes data, geology, tectonics, fault activity and 7 seismic source zones in the southern Dead Sea Transform and Gulf of Suez were determined in this study. The seismic hazard parameters namely the b-parameter, annual activity rate and upper bound magnitude were determined for each determined seismic zone. The outputted maps of Peak ground acceleration (PGA) values with a 90% probability of not being exceeded in 50 years were determined for the Gulf of Aqaba regions. These indicated the PGA values of around 0.293 g using Ambraseys equation and about 0.286 g using Boore equation in the central part of the Gulf. The maps have been calculated using EZ-FRISK (version 7.25) program.

CHAPTER 1

INTRODUCTION AND OBJECTIVES OF STUDY

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INTRODUCTION AND OBJECTIVES OF STUDY

1.1 Introduction

The Northern tip of the Gulf of Aqaba area is undergoing rapid development, involving two planned huge projects, i.e. the Red Sea –Dead Sea canal and the first Jordanian civil nuclear power plant, although this later project seems less probable now. Yet this area is part of the plate boundary between the Arabian and the African plates, Aqaba is just laying on this plate boundary of the transform type and composed of a number of pull-apart basins bordered by seismically plate boundary class active faults. The area is obviously prone to seismic hazard, in need of being properly evaluated.

Seismicity, seismotectonics and seismic hazard assessment are more than ever necessary. This research will constitute robust basis to help preparing reliable input data for any successful mitigation of the seismic hazard and the efficient minimization of losses in case of a strong earthquake which is always probable in this kind of active plate boundary areas.

Seismic hazard assessment is an important input to evaluate seismic risk at a specific site. Minimization of the losses of life and propriety due to earthquakes depend among other factors on good estimates of seismic hazard parameters. As a result, this study is concerned the reliable estimation of the seismic hazard parameters as a necessary step towards seismic risk evaluation of the study area.

2.1 Previous studies

Various components of the Gulf of Aqaba’s seismicity were studied. The first instrumentally recorded swarm in the gulf (1983) was analyzed by El-Isa, et al., (1984) who gave a qualitative general location and first tentative interpretations of the swarm

in its tectonic context. Abou Karaki (1987,1995, 2001) used local and regional data to carry out relocations and focal mechanism computations for the 1983 swarm, analyses of the location and dispersions in the evaluation of the magnitude related to the Mw =7.3 Gulf of Aqaba earthquake of November 22 1995. The contributions of the surrounding seismological stations were also analyzed in the framework of a general study of the efficiency of the seismological stations involved in the location of the event. Abou Karaki, et al., (1993) further discussed the 1983 swarm. Al-Qariouti (1990) studied the characteristics revealed by the Gulf of Aqaba few first instrumental earthquake swarms; Al-Qariouti (2002) also analyzed earthquake strong motion data of the Gulf of Aqaba activity for 1993-2001 and their engineering implications. Al-Tarazi (1992) included the Gulf of Aqaba in his evaluation of the seismic hazard related to the Jordan Dead Sea Fault segments; Ambraseys, et al., (1994) gave a confused account of the area's historical seismicity; Klinger, et al., (2000) studied the co-seismic deformation during the Mw 7.3 Aqaba earthquake (1995) from ERS-SAR interferometry.

In 1995, seismic hazard maps for Peak Ground Acceleration on bed rock site with 90% Probability of not being exceeded for an economical life time of 50,100 and 200 years were developed for Al-Karak city in Jordan (Malkawi, et al., 1995).

The development of seismic hazard assessment in Jordan and adjacent areas were studied involving iso-acceleration contours of maximum seismic intensity (Al-Tarazi, 2000), and peak ground acceleration (Al-Tarazi, 1992, 1999; Batayneh, 1994). These studies used the probabilistic method and evaluated the hazard for the main Jordanian cities but without taking into consideration local site conditions. They have used attenuation equations of PGA developed for other regions in the world (for example McGuir, 1976 equation).

Al-Amri, et al., (1991) studied the Seismicity and Aeromagnetic Features of the Gulf of Aqaba Region, Dahy (2010) used all available information to Study on Seismicity and Tectonic Setting in the Northeastern Part of Egypt including the Gulfs of Suez and Aqaba.

Al-Zoubi, et al., (2006) examined the location of the strong events in Dead Sea Transform and correlated them with the various tectonic elements in the area. Hamouda (2009) evaluated the seismic hazard for Nuweiba city in Gulf of Aqaba, the aftershock sequence of the Gulf of Aqaba earthquake recorded by short period and broad band stations between November 1995 and December 1996 was analyzed by (Hofstetter, 2003).

Korrat, et al., (2006) studied the Seismicity in the northernmost part of the Red Sea and relocated some events to obtain a better picture for the seismicity of the area.

Abdel-Rahman, et al., (2009) defined the seismogenic zones that might affect the Sinai Peninsula (including Gulf of Aqaba) depending on the distribution of earthquakes and calculated the a and b parameters in the framework of studying the seismicity of Sinai Peninsula.

3.1 Objectives of study

From engineering aspects and for seismic microzonation studies, seismic hazard assessment is a necessary step to estimate the seismic risk. The seismic hazard can be expressed as a relationship between the level of the seismic effect and the corresponding probability of occurring.

The purpose of this work is to help clarifying the seismicity issues in the Gulf of Aqaba

The main objectives of this research are specifically:

1. Relocating, reanalyzing, and reassessing available instrumentally recorded earthquakes and correlating the new results with previously determined results.
2. Producing a revised and updated earthquake catalogue for instrumental earthquakes covering the period 1900-2010.
3. Testing the efficiency of the seismological stations involved in the location processes and suggesting robust station corrections whenever possible and necessary.
4. Analyzing and displaying the integrated seismicity results in maps and in a synoptic fashion and integrating them along with the relevant geological, tectonic, and geophysical data within a GIS system.
5. Producing hazard map of the Aqaba region showing peak ground acceleration (PGA).

CHAPTER 2

SEISMOTECTONIC SETTING OF THE GULF OF AQABA

CHAPTER 2

SEISMOTECTONIC SETTING OF THE GULF OF AQABA

2.1 Introduction

Early plate tectonic models identified the southern corner of Sinai as lying near a rift–rift transform (or the general type Ridge-Ridge-Fault, "RRF" triple junction: Le Pichon, et al., 1973; Turcotte and Schubert, 2002) between the Red Sea, Gulf of Suez and Gulf of Aqaba.

Sinai Peninsula is bounded from the west by the Gulf of Suez and the Suez channel and from the east by Gulf of Aqaba, while it is bordered by the Mediterranean Sea from the north and the Red Sea from the south. The geology and tectonics of Sinai is largely affected and controlled by the geodynamic processes acting in the Red Sea with its northern bifurcations and eastern Mediterranean regions (figure 2.1).

The Red Sea is one of the world's youngest oceanic basins that separates the Arabian plate from the African plate. It's a □ N30°W (with respect to the Bab el Mandeb, Ridge-Ridge-Ridge, "RRR" triple junction) trending depression about 2000 km long (El-Shazly, 1982).

At the northern part of the Red Sea it splits into the opening of the Gulf of Suez and the Gulf of Aqaba-Dead Sea transform system dominated by sinistral shear (Ben-Menahem, et al., 1976, who used the absolute term "rift" to describe the system). It is supposed that these depressions were formed by the anticlockwise rotation of Arabia away from Africa about a pole of rotation in the central or south-central Mediterranean Sea (Le Pichon and Gaulier, 1988).

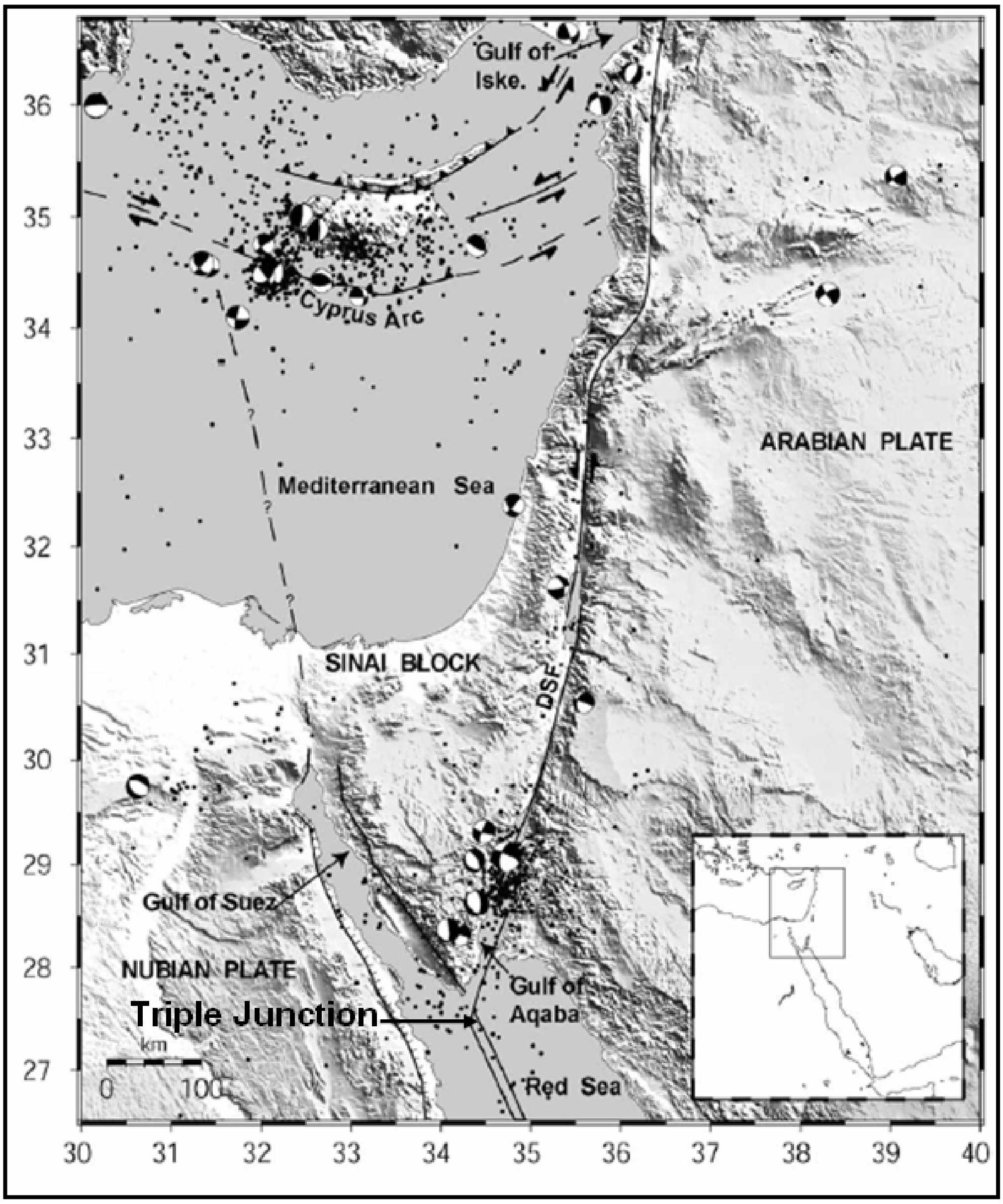


Figure 2.1: General tectonic setting of the Sinai-Palestine subplate and surrounding area (Slightly modified after Mahmoud, et al., 2005).

2.2 Tectonic setting in the Gulf of Aqaba-Dead Sea Transform

The tectonics of the Middle East is controlled by the Dead Sea Transform (DST) fault system, a major morphotectonic structure that forms the North western boundary between the Arabian plate and the African plate (figure 2.2) (Quennell, 1959; Garfunkel, 1981; Garfunkel, et al., 1981; Kashia and Crocker, 1987). It is responsible for most recent structures of the region (Quennell, 1958; Garfunkel et al., 1981; Abou Karaki, 1987). Figure 2.3 shows the tectonic structures in and around the Arabian plate, including Gulf of Aqaba DST.

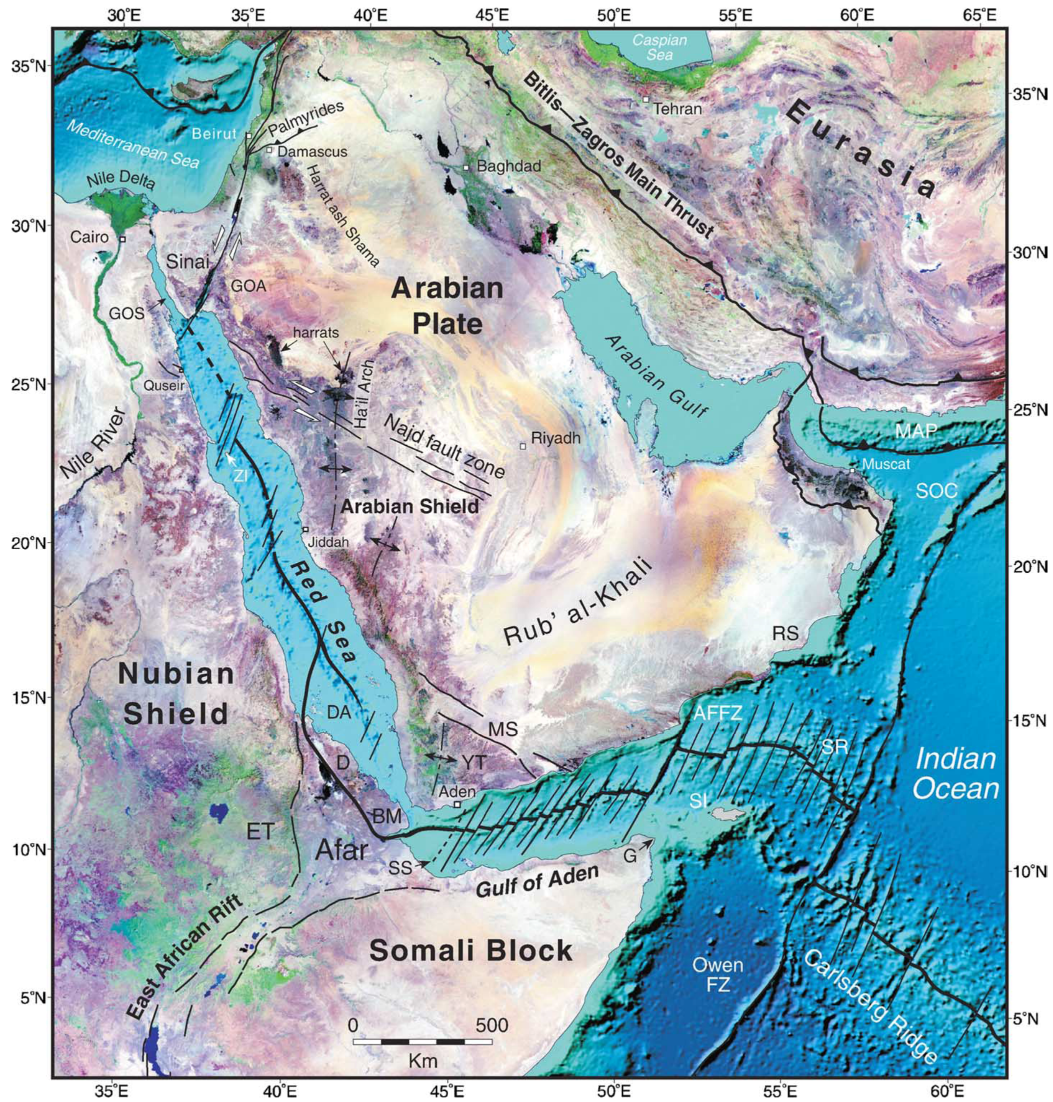


Figure 2.2: Location of Jordan-Dead Sea Transform in relation to Arabian Plate and Sinai Subplate (Smith and Sandwell, 1997).

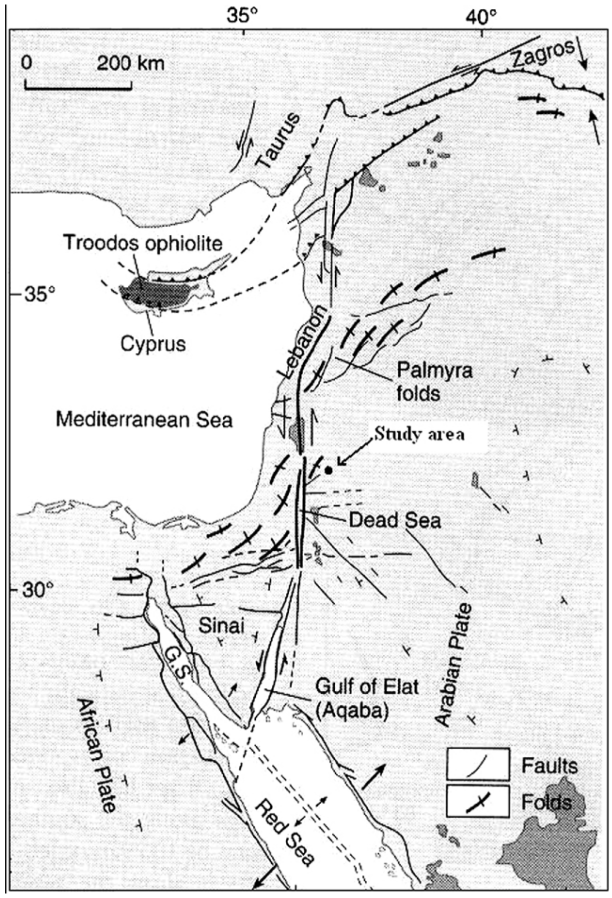


Figure 2.3: Tectonic structures in the Middle East including Gulf of Aqaba (modified after Garfunkel, 1981).

The DST fault is about 1000 Km long sinistral strike-slip fault system that connects the active centers of sea floor spreading in the Red Sea area to the convergence zone in the Taurus Mountains in Turkey. It is a major source of seismic hazards in the Eastern Mediterranean and North-western Arabia (Abou Karaki, 1987).

The left lateral shear motion along the DST is considered to be a response to the extensional opening of the Red Sea (Girdler, 1985).

The DST fault was initiated in the Middle Miocene around 20 M.Y ago (Quennell, 1958; Freund, 1965; Garfunkel, et al., 1981; Bartov, et al., 1980). The initial movements along the Dead Sea transform were nearly pure strike-slip, but in post- Miocene time they may have changed to strike-slip with a small component of oblique extension resulting in the opening of basins along the DST (Garfunkel, 1981)

and even some small reverse components in the northern Gulf of Aqaba area (Abou Karaki,1987; Abou Karaki, et al., 1993; Abou Karaki,1995) this latest result was clearly suggested by analyses of the composite fault plane solution of the main events of the Gulf of Aqaba swarm of 1983 (figure 2.4).

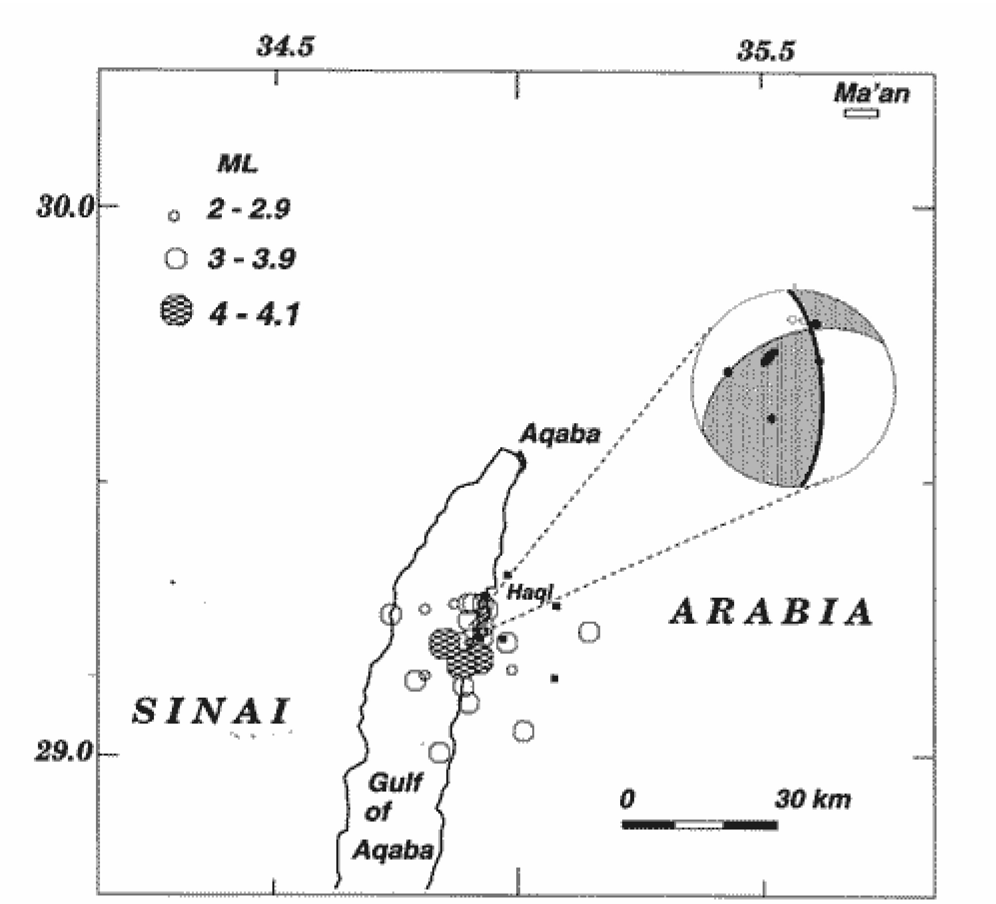


Figure 2.4: The composite fault plane solution of the 2 main events of 1983 swarm (Abou Karaki, 1987, 1995; Abou Karaki, et al., 1993).

Since the time of its formation, about 107 km of left lateral horizontal movement has occurred along the Dead Sea transform fault in two stages (Quennell, 1958; Garfunkel, 1981; Al-Zoubi, 2003). The first one involved a horizontal displacement of about 62 Km during the Lower Miocene (Quennell, 1958, 1959; Freund, et al., 1970).

The second movement resulted in a horizontal displacement of about 45 km, which took place during the Plio–Pleistocene (Quennell, 1983). Along the southern half of the transform, the strike-slip motion takes place on en-echelon faults. This produces rhomb-shaped grabens or pull-apart basins, which are sometimes composite, and in which there is local crustal separation. Thus, much of the transform is (leaky).These structures occur in a morpho-tectonic “rift-valley” delimited by normal faults, which express a small component of transverse extension (Garfunkel, 1981).

The slip rate of DST is in the range between 1- 10 mm per year (Garfunkel, et al., 1981; Klinger, et al., 2000; Gomez, et al., 2003; Pe’eri, et al., 2002; Meghraoui, et al., 2003; Le Beon, et al., 2008; Ferry, et al., 2007, 2011).

Global plate model indicated a faster differential motion (10–15 mm/ year) between African and Arabian plates. The difference in the velocity of the plate motion along the plate boundary could be related to the fault segmentation. As a result, Dead Sea fault system comprises at least 15 fault segments with lengths ranging between 25 and 55 km (ten-Brink, et al., 1999). Some of the fault segments are buried and do not offset the upper sedimentary section (Al-Zoubi, et al., 2002; Frieslander, et al., 1996).

Regional uplift and basaltic volcanism are characteristics of the DST and the Red Sea region. More than 3 km uplift is believed to have taken place in the Red Sea since the Oligocene (Garfunkel, 1981). In the Dead Sea region, uplift is about 1-2 km.

The Gulf of Aqaba is the southernmost part of DST, it is 30-40 km wide and about 180 km long depression reaching a maximum depth of 1850m, (http://en.wikipedia.org/wiki/Gulf_of_Aqaba).

Nowadays (from 1983 to 2011) the Gulf of Aqaba has been the most seismically active zone of the DST boundary (figure 2.5).

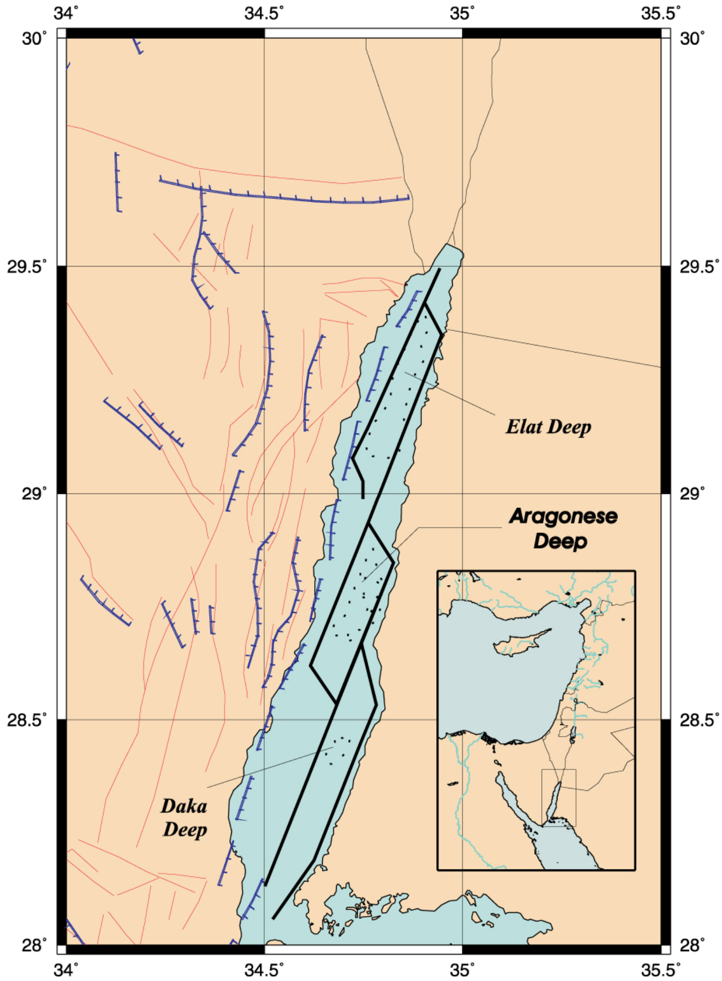


Figure 2.5: Location of the Gulf of Aqaba in relation to DST showing the en-echelon grabens which compose the Gulf of Aqaba depression (Ben-Avraham , 1985; Ben-Avraham, et al., 1996).

Based on geological and geophysical data, it was suggested that the depression of the Gulf of Aqaba has been formed by extensional tectonics (Ben-Avraham 1985).

The tectonic setting of the Gulf of Aqaba is closely related to the Dead Sea Transform fault region (Al-Zhoubi, et al., 2006). The evolution of the Gulf started with the initiation of the Red Sea rift in Late Oligocene to Early Miocene, the displacement motion along the main fault has been continuous since that time, with increase in the component of transverse separation along the DST since 5 million years (Joffe and Garfunkel, 1987). The age of the Aqaba Gulf is a late Miocene-Pliocene age (Hosney, 1985).

The Gulf of Aqaba faulting structure is dominated by vertical to sub-vertical faults with principal directions of NNE-SSW, NE-SW, E-W and NW-SE (Rashdan, 1988) figure 2.6.

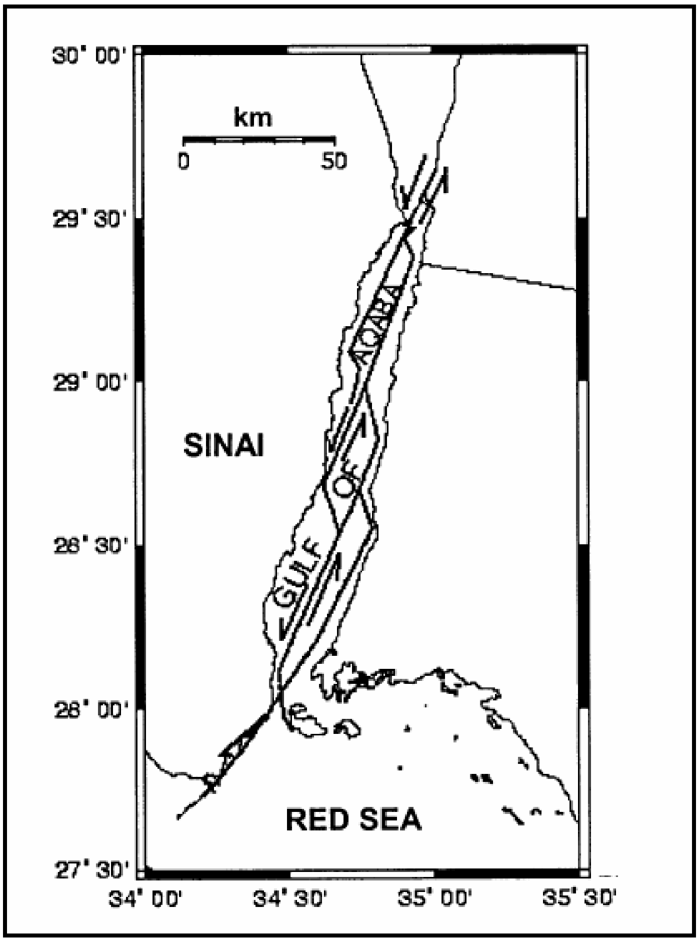


Figure 2.6: Principal directions of faults of Aqaba structure (after Bayer, et al., 1988).

These fault systems resulted in the creation of three en-echelon rhomb-shaped grabens, and these grabens are filled with a few kilometers of sediments (Hamouda, 2009).

The en-echelon depressions interpreted as pull-apart basins with different sizes (figure 2.5). The two longitudinal sides of such basins are bounded by the segments of the en-echelon strike-slip faults that have dip-slip components, while the other two sides are being normal faults trending diagonally to the strike slip faults (Al-Qaryouti, 2002).

The northern part is the largest basin and the shallowest area of the Gulf; it is about 900 m depth. It is dominated by the flat-bottomed Aqaba (Elat) deep, about 50 km long and 3–8 km wide. The central basin (Aragonese deep) is about 35 km long and 6 km wide. It includes the deepest points in the Gulf (about 1,850 m), which are separated by shallow basin sill. The southern part of the basin is about 55 km long and 6 km wide, and includes the Dakar (1,400 m) and Tiran (1,300 m) deeps (Hall and Ben-Avraham, 1978; Ben-Avraham, 1985) (figure 2.5). Part of the complexities of tectonic processes in the northern Gulf of Aqaba are identified and shown in figure 2.7 some elements in the figure confirm and support the existence of a component of compressional tectonics in the area first revealed by Abou Karaki in the composite focal mechanism of the Gulf of Aqaba swarm of 1983 (Abou Karaki, 1987, 1995, Abou Karaki, et al., 1993).

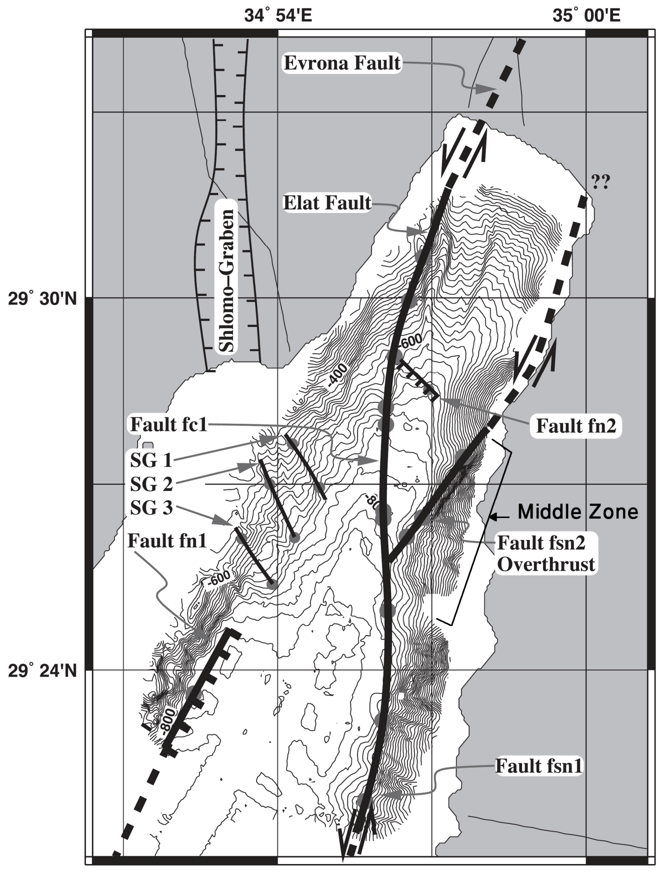


Figure 2.7: Tectonic map of the northern part of Gulf of Aqaba
(Ehrhardt, et al., 2005).

From figure 2.7, it is noticed that in the northern part of the Elat Deep, the Main trend of the DST correlates with the eastern boundary fault (fsn1) which has a left lateral strike-slip motion and a significant normal component. The western boundary normal fault (fn1) terminates and does not continue as attested by the bathymetry, which was interpreted by (Ehrhardt, et al., 2005), as indicating the absence of strike-slip faulting.

The main strand of the DST continues into the middle Zone, where the left step over occurs. The SG1, SG2 and SG3 faults which has SE–NW trend, result from the junction between the so called Shlomo Graben and the Gulf of Aqaba, and don't show any displacement related to strike slip faulting. This result confirms the interpretation of fault fn1 as normal. Close to the inflection point, the bifurcation of the main strand of the DST into the faults fc1 and fsn2 can be observed. Fault fsn2 splits from fsn1 and bends right. Fault fc1 strikes toward the western side of the northern edge of the Gulf, where it correlates with Elat Fault and its onshore continuation in the Araba Valley, the Evrona Fault (Reches, et al., 1987; Ben-Avraham and Tibor, 1993). The fault fc1 show stratigraphic displacement because it links fault fsn1 and the Elat Fault.

According to the interpretation of (Ehrhardt, et al., 2005), the strata between the bounding faults are subdivided by the unconformity into lower (pretectonic) and an upper (syntectonic) unit. Parallel horizons and an undisturbed internal structure are signaling a tectonic quite time and pure strike-slip without extension or compression during the pretectonic phase. The second syntectonic phase, which begins in the early Pliocene, is characterized by a major change in the activity of the DST. The pretectonic sedimentary unit subsided and dips southward with inclination to the east (Ehrhardt, et al., 2005).

2.3 General geology of the study area

The basement rocks in Jordan are divided into the Aqaba complex and the Araba complex that are separated by a regional unconformity.

Aqaba complex forms part of the Precambrian Basement of southern Jordan which represents the northern most exposed portion of the Nubian-Arabian Shield (Bender, 1974). The Aqaba complex is composed of diabasic rocks and post-plutonic intrusion, and distinguished by the existence of olive green dikes. Aqaba complex consists of two units:

1) Metamorphic Rocks are found as blocks within the surrounding intrusive rocks with a maximum age of 700-800 M.Y (Jarrar, et al., 1983).

2) Igneous Rocks which consist of highly weathered granites, granodiorites and quartzdiorite. The plutons of the Aqaba complex have an average of 630-580 M.Y (Ibrahim and McCourt, 1995).

The outcrops of sedimentary rocks of the area consist of alluvium, sand dunes, sandstones, clay, conglomerate and reef coastal deposits, and ancient dunes. The age of these rocks is Quaternary.

Rashdan (1988) characterized three lithological units (figure 2.8), which are outcropping in Aqaba area:

(a) Kurnub Sandstone Group (Mesozoic Age): this unit is outcropping in the approximately 4-5 km southeastern Aqaba City. It comprises a soft gray-white fine to coarse-grained sandstone with rounded quartz granules. It is consistent with a continental fluvial depositional environment.

(b) Pleistocene gravels (Quaternary Age): gravels of Pleistocene age occur in Wadi Araba and Aqaba Area in the northern and southern parts of Aqaba City.The gravels have been preserved from erosion by being down faulted into mini grabens. The Kurnub

Formation has similarly been preserved beneath the gravels in the southernmost outcrop. The gravels consist of granitic cobbles and pebbles set in an uncemented matrix of finer unsorted material.

(c) Alluvium and wadi sediments (Quaternary Age): It occurs in the northern part of the city, including various facies of unsorted to sorted alluvium. The alluvial fans are distinguishable from the active wadi sediments by retaining an incipient desert varnish. Coral formation occurs at some localities along the Aqaba shore.

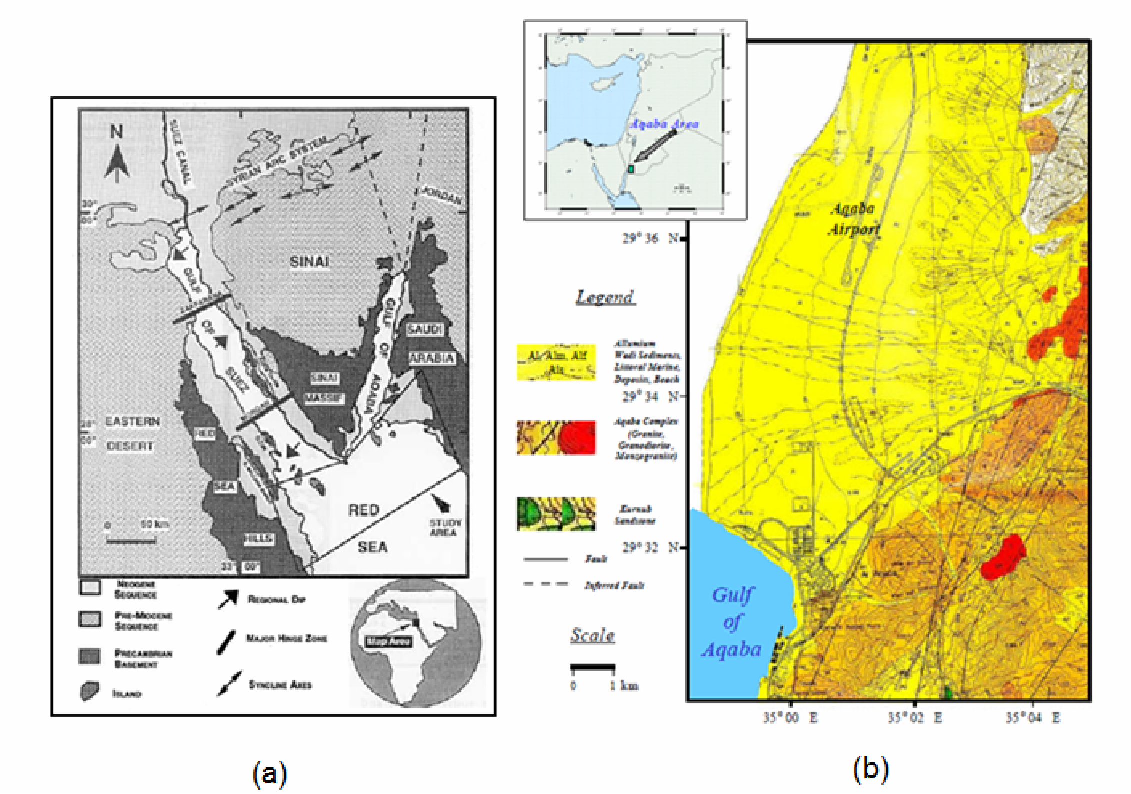


Figure 2.8 (a) Simplified general Geological map of the Gulf of Aqaba and Sinai area (Alsharhan and Salah, 1997). (b) Geological map of northern part of the Gulf of Aqaba (Modified from Rashdan (1988)).

CHAPTER 3

SEISMICITY OF THE GULF OF AQABA IN THE FRAMEWORK OF THE DEAD SEA TRANSFORM SYSTEM

CHAPTER 3

SEISMICITY OF THE GULF OF AQABA IN THE FRAMEWORK OF THE DEAD SEA TRANSFORM SYSTEM

3.1 Introduction

The most important aspects of seismicity are given by the geographic distribution of earthquakes, depth, magnitude, and their occurrence over time, mechanisms and the damage produced by them.

The Dead Sea fault system and its branching faults are associated with the highest concentration of earthquakes in the region. The seismic activity along the DST during the last two decades was characterized by earthquake swarms, especially in Gulf of Aqaba.

The seismicity of the DST is concentrated in the deep depressions occupied by the Gulf of Aqaba and the Dead Sea. Little activity is observed along the Wadi Araba segments of the fault. North of the Carmel Wadi Fara'a fault system, the seismic activity is scattered on the western side of the transform, some of this scattering may be an artifact caused by the distribution of seismological stations involved in the location process with respect to the transform. Towards the north, most of the activity was associated with the western secondary branches of the transform (The Roum Fault and its surroundings) culminating with the ~ Ms 6 earthquake of 16-April 1956 which caused widespread destruction in thousands of villages in Southern Lebanon and northern Galilee (Roche,1969), in 2008 the activity resumed in almost the same general area culminating on Feb. 15 by an M= 5.1 earthquake followed by hundreds of less magnitude events (http://www.cnrs.edu.lb/RapportduCNRS-SeisSouth.pdf) (figure 3.1).

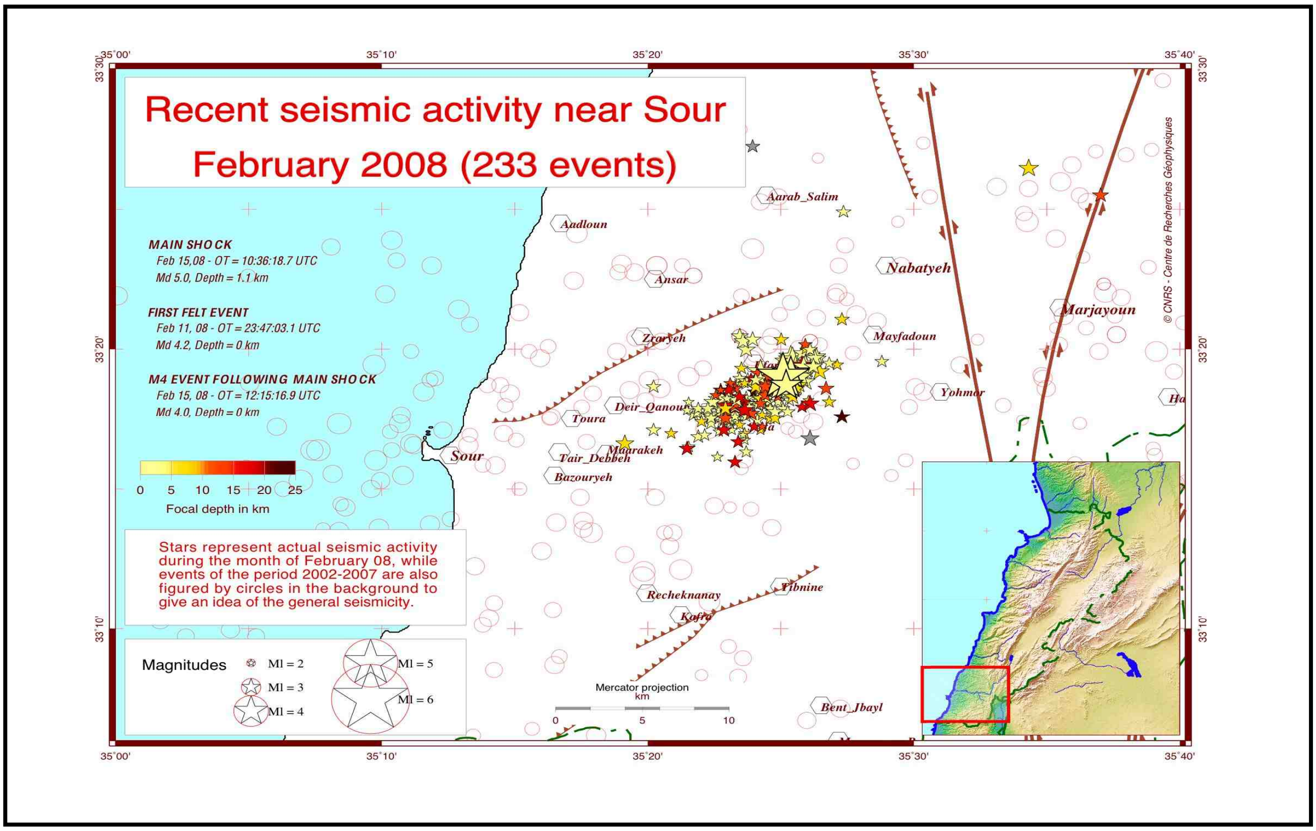


Figure 3.1: Seismic activity in the northern part of DST in 2008.
(http://www.cnrs.edu.lb/SeismeSouth.html).

There was little seismic activity over the past century along the historically more active Yammouneh fault and its northward continuation (figure 3.2) Poirier, et al., (1980), Abou Karaki (1987). This is also true by now.

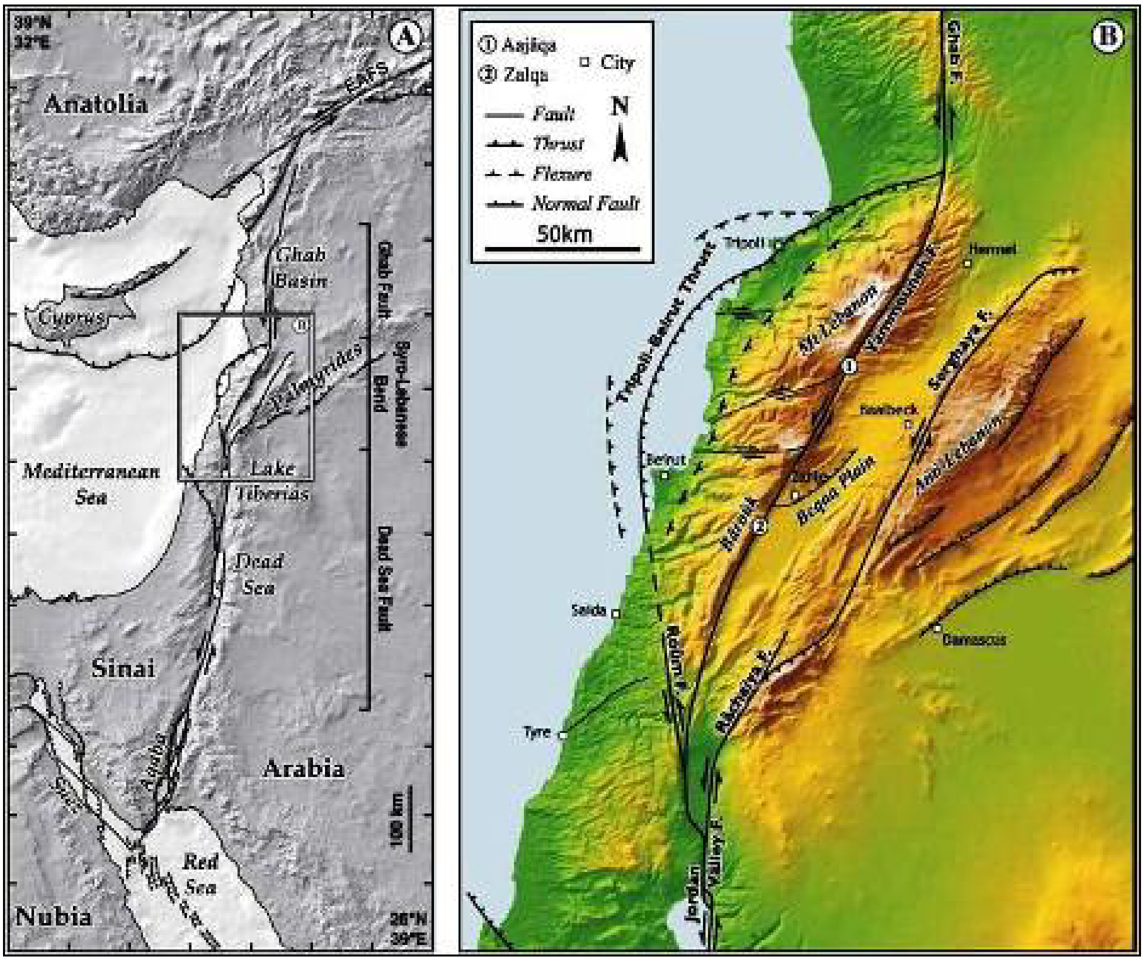


Figure 3.2: Tectonic setting of northern part of Dead Sea Transform Fault (Daeron, et al., 2004).

Although there are different focal mechanisms along the transform system, the fault plane analyses of the major earthquakes confirm the left lateral nature of the system as a whole (Maamoun, 1976; Abou Karaki, 1987; Salamon, et al., 2003; Hofstetter, et al., 2007).

3.2 Historical Seismicity

Damaging earthquakes have occurred in the DST region in historic and prehistoric times and this was a subject of research in many historical seismicity and archaeoseismicity studies (Willis, 1928,1933; Sieberg, 1932; Ben-Menahem, 1979,1991; Russell , 1985; El-Isa and Mustafa, 1986; Abou Karaki, 1987; Al-

Tarazi, 1992; Ambraseys, et al., 1994; Jaber, 1994; Guidoboni, et al., 1994,2005; Galli,1997,1999; Galli and Galadini , 2001) (see figure3.3).

Also the area is starting to be relatively well covered by paleoseismicity studies (Reche et al., 1981; El-Isa and Mustapha, 1986; Neimi, et al., 1999, 2001; Neimi, 2004; Le Béon, 2008; Ferry, et al., 2007, 2011). The largest reported historical earthquake magnitude in the Dead Sea transform region is of the order of 7.6 (corresponding to the northern Lebanon earthquake of may 20 1202, Ambraseys and Melville (1988). Al – Sa'adani, 1971; Poirrier and Taher, 1980; Taher, 1979. collected the historical earthquakes of the Middle – East area during the period from the seventh to the eighteenth century based on arabic manuscripts. The macroseismic epicentral distribution of historical earthquakes seems to correlate with the general tectonics of the region.

There are many somewhat confused accounts of historical seismicity in the Gulf of Aqaba area, some of the reported historical earthquakes there proved to have no relation with the area, as they were only based upon very questionable data, the most clear example of this is the earthquake of Ramla 18 March 1068 which was associated with the region of Tabouk in Northwestern Arabia (Ambraseys, et al., 1994) (see figure 3.3).

In this work, the historical seismicity catalogue of Abou karaki (1987) will be adopted as it represents the most robust work about the historical seismicity problems in the area. In Abu Karak´s work all the earthquakes were checked and subjected to a process aiming to clean the historical seismicity data from duplications and misinterpretations (Abou Karaki, 1995).

The following list (table 3.1) which is based on a revised version of Abou Karaki (1987) and Abou Karaki (1995), represents the historical earthquakes that

affected Aqaba or were associated with the Gulf of Aqaba segment of the Jordan Dead Sea Transform and also those which were associated with the Wadi araba Northern continuation of the Aqaba system.

Table 3.1: Historical seismicity affecting the Gulf of Aqaba for the last 2000 years After Abou Karaki (1987).

Date	Latitude(°)	Longitude(°)	Affected location in order	Intensity class	Magnitude	Fault Segment(s)
48	30	35.2	Jabal Rum, Petra, Tal El-Khalaifeh	2	6.5	WAR/GAQ
748 AD = Ramadan 130 AH.	32	35.5	Jerusalem (2), Tiberias(2), Lod (2), Jerash (2), Jericho(2), Arad(2), Damascus(1), Syria(1), Egypt (1), Arabia (1), Mesopotamia (1)		7.0	JVA (PS) A minimum of 3 Shocks.
1047/ 48 439 AH	31	35.5	Ramla	2	6.0	JVA/WAR
18 03 1068	31.5 30.0	35.5 35.0	Ramla (2), Banias (2), Jerusalem Aqaba(2), Tabuk(1), Tayma (1) Khaibar(1), Wadi Es Safra (1), Egypt (1)	2	7.0 6.5	JVA WAR/GAQ
1156/59	31	35	Petra (2), Bethlehem(1), Egypt (1)	2	6.5	WAR
2 05 1212	30	35	Aqaba-Elat (2), Shobak (2), Karak(2), Cairo (2), Egypt(2)	2	6.5	WAR/GAQ
1261/ 1262	30	35	Karak, Shobak, Cairo		6.0	WAR
Jan/Feb 1293	31	35.5	Karak (2), Ramleh(2), Gaza(1),Lod (1)	2	6.0	WAR
1458/ 1459	31	35.5	Karak (2) 100 victims in Karak	2	6.0	WAR
5 01 1588	30	35	Aqaba (2), Cairo(2), Egypt, Sinai	2	6.5	WAR/GAQ

* Intensity classes: 1= Non destructive [III,VI]. 2= Destructive [VII-IX]. 3 = Very Destructive [X-XII]. (Abou Karaki,1987).

A brief description of the main historical earthquakes is summarized below including other researcher's ideas about some of these earthquakes when available:

The earthquake of Ramadan 130 A. H. (748 AD, Abou Karaki, 1987) was reported by Ben Menahem (1979) to have occurred in 746 A. D. and in some references the earthquake time is reported to be 749 AD. (Marco, et al., 2003) a macroseismic epicenter in the Jordan valley and maximum effects up to a distance of a bout 30 km from the "epicenter". Marrco, et al. (2003), stated that this earthquake caused kilometric surface ruptures in Mesopotamia several hundred kilometers from the epicenter, further more evidences of destructive effects of this earthquake were suggested by Donald Whitcomb in his archeological excavations of 1993 in Aqaba that a mosque was reconstructed as other parts of the city in the Abbasid period (in Whitcomb so called phase B, 750-850 A.D.). The mosque "was part of the reconstruction of the city after the 748 earthquake". (http://oi.uchicago.edu/research/projects/aqa/)

To summarize: This earthquake occurred in the northern part of the Jordan Valley. It was an ML =7.0 class earthquake at least, with great damage in and around the Jordan Valley, Tiberias, Gadara. Severe damage was reported at Pella, Jerusalem, Jerash and Lod. Tsunami on Mediterranean coast. Seiche in the Dead Sea. (Hasweh, 2000).

An other important and controversial earthquake is the one of 11 Jumada II 460 AH corresponding 18 March 1068 A.D, located around (30˚N, 35˚E) with a radius of uncertainty of 150 km (Abou Karaki, 1987). It caused major damage from the Banyas area (some 400km north of Aqaba where about 100 people were reported to had been killed) to Hejaz, and the ancient city of Ayla which was completely destroyed. It was reported that all inhabitants of Ayla excepted 12 of them were killed by the earthquake

(Abou Karaki, 1987; Ambraseys, et al., 1994 and their references based on Arabic documents).

In 27 Dhulq. 608 A.H. 2 May 1212 A.D. an earthquake occurred in Southern Palestine with ML= 7 (Ziberman, et al., 1998), this particular earthquake was located in the southern Wadi Araba around (30˚N, 35˚E) with a radius of uncertainty of 150 km (Abou Karaki, 1987), and a magnitude of at least 6.5 (Abou Karaki, 1987). It caused damage of many houses at Al–Shaubak and Al–Karak in Jordan. The earthquake was also reported to have been destructive in Egypt (Cairo) (Abou Karaki, 1987; Ambraseys, et al., 1994).

The (Safar 692 A. H.) January/February 1293 A.D earthquake was destructive in Ramla and Karak, it also affected Gaza and Lod. The event was located around the southern tip of the Dead Sea around (31˚N, 35.5˚E) with a radius of uncertainty of 150 km and a minmum magnitude of 6 (Abou Karaki, 1987). A magnitude of about 6.5-7 was assigned to this event in the work of (Ambraseys, et al., 1994).

An other earthquake 4 Safar 996 A.H (5 January 1588 A.D Gregorian Calendar) may have occurred in the area of the Gulf of Aqaba. The location of this earthquake is not well established, and could be either related to Wadi Araba around (30˚N, 35˚E) with a radius of uncertainty of 150 km (Abou Karaki, 1987), or to the Gulf of Aqaba segments of the transform (after Ambraseys, et al., 1994).

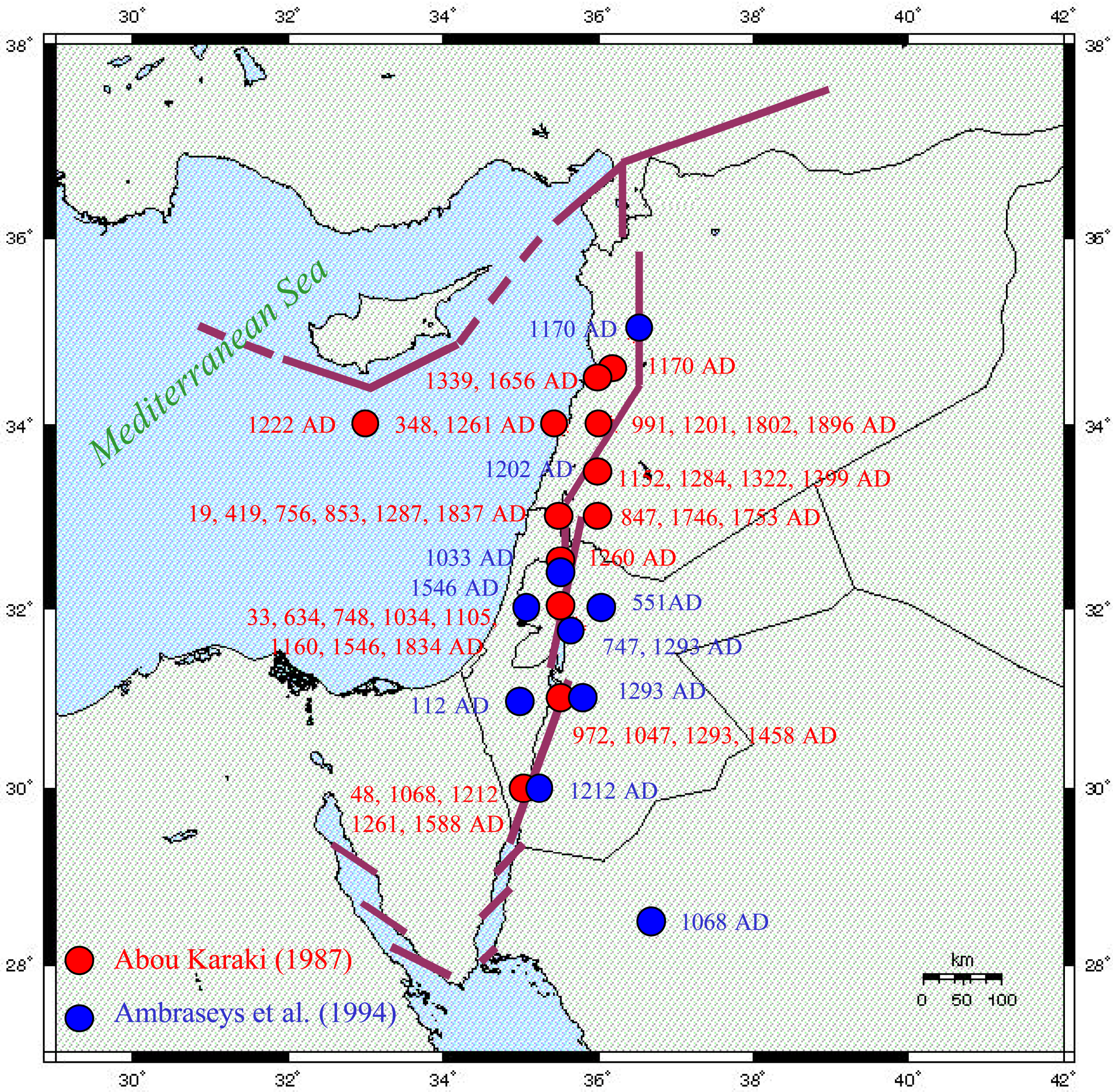


Figure 3.3: Comparison of historical seismicity data of the Jordan Dead Sea Transform after Abou Karaki (1987) and Ambraseys, et al. (1994). Figure taken from Al-Qaryouti (2002).

3.3 Instrumental Seismicity

The numbers of seismological stations around the DST fault have increased and with time many catalogues of the instrumentally recording earthquakes have been published Ben-Menahim, 1979; Arieh, et al., 1985; Hasweh, 1986; Abou Karaki, 1987; Al–Tarazi, 1992; and Shapira and Shamir, 1994.

Instrumental seismicity monitoring in the Jordan-Dead Sea region and the surrounding area started in 1899 with the installation of the Helwan seismological

station in Egypt. In 1910, the Ksara station in Lebanon was operated followed by installation of a seismic station in Istanbul in Turkey in 1935 (El-Isa, 1981).

In the Dead Sea region, the local instrumental monitoring began in 1964, with installation of two seismological stations; one was installed in Jerusalem and the other in Safad (Arieh, et al., 1985).

In Jordan, the first seismological station was installed in the Geology Department / University of Jordan in Amman in 1981. This station consists of a three component short period seismograph. Between 1982 and 1983, systematic regular monitoring was started by the installation of seismological stations of the Institute for Petroleum Research and Geophysics (IPRG), west of the Dead Sea area, and the Jordanian Natural Resources Authority (NRA), east of the DST.

The seismic activity is concentrated along the DST. Three major events have been recorded from 1900 up to 2011 south of the Lake Tiberias along the DST. The first occurred in July, 11, 1927, it was located by the ISS (the British International Seismological Summary – ancestor of the Nowadays International Seismological Center ISC near Jerico in the Jordan valley (32N, 35.5E) and assigned a magnitude of 6 1/4. This earthquake was studied by Ben-Menahem, et al. (1976) and further analyzed in detail in Abou Karaki (1987, 1999). 342 Persons were reported to have been killed because of building collapses on both Jordan and Palestine area (Sieberg, 1932). The second one was in 1993, and the third was in 1995.

The Gulf of Aqaba region was affected by four major earthquake swarms; the first one started on January 21, and lasted to April of 1983. There were 181 earthquakes listed in the IPRG Bulletin and 60 shocks from the swarm were recorded by the Jordan University Seismological station (Figure 3.4). The swarm took place entirely outside the IPRG stations network. The Gulf of Aqaba swarm was studied by (El-Isa, et al., 1984),

using data of the UNJ (University of Jordan seismological station) and of 6 portable vertical component stations which were distributed around the Saudi Arabian town of Haql on the eastern side of the Gulf of Aqaba. Using data of the 6 Haql stations (Bazzari, et al., 1990) studied the post swarm events and relocated 191 of them, half of the new locations were found to be inside the Gulf. 42 events were relocated by (Abou Karaki, 1987), their location was found to be associated with the eastern coast of the Gulf of Aqaba. The largest shock had a local magnitude of 5 and about 10 events had a magnitude greater than or equal to 4.4 (El-Isa, et al., 1984). About 94 earthquakes of magnitude ML>3 mostly confined to the Eilat basin. (Al-Qaryouti, 2002).

The second swarm occurred on April 20 – 27, 1990 in the southern part of the Gulf of Aqaba with a peak magnitude of ML = 4.2 (figure 3.5).

The third sequence started on July 31, 1993, and continued until the end of August, 1993 (figure 3.6). More than 600 events occurred and 420 events of magnitude equal to or greater than 3(Shamir, 1996). The largest shock had a magnitude of ML = 5.8 (Mw = 6.1).(Al-Qaryouti, 2002)

The fourth swarm started on November, 22 in 1995; the largest earthquake sequence of main shock-after shock type began in the central part of the Gulf of Aqaba and continued until December 25, 1998 (figure 3.7). The main event (Ml=6.2, Mw= 7.1) was followed by more than seven thousand after shocks within 100 days (Klinger, et al., 1999). The Waveform inversion of this event suggests a nearly pure strike-slip mechanism with about 1.6 m of left-lateral slip along 80 Km fault zone striking N20°E (Klinger, et al., 2000). Figure 3.8 show the focal mechanism for 1983, 1993 and 1995 earthquakes.

Most of the aftershock activity is concentrated north of the main shock in the Aragonese and Eilat basins, while the activity is diffuse south of the main shock in the

Dakar and Tiran basins (Hofstetter, 2003). Most of the moderate to strong aftershocks of the whole aftershock sequence occurred in the Aragonese basin, mainly in the first 100 days following the main shock. The Eilat basin is characterized by a larger number of aftershocks composed mainly of small magnitude earthquakes (Hofstetter, 2003; Al-Zoubi, et al., 2006). The 1995 sequence was the most important and energetic on the whole Dead Sea transform area during the instrumental seismicity era. Table 3.2 have a list of some useful information related to 1983, 1993, and 1995 swarms.

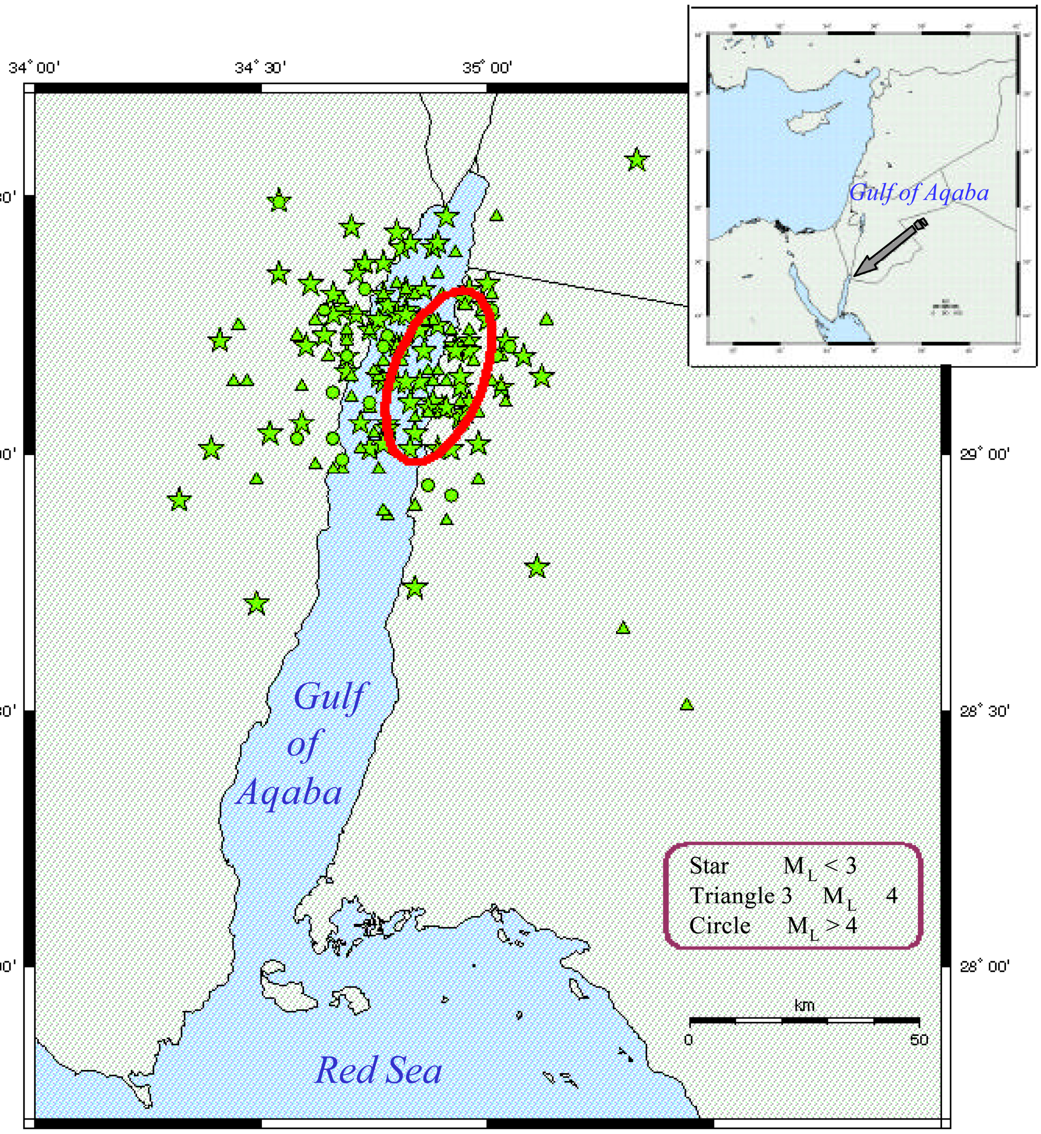


Figure 3.4: Epicentral distribution of the Gulf of Aqaba 1983 swarm as located by the IPRG bulletin 2. The ellipse shows the area where most of the relocated 42 events were found by (Abou Karaki, 1987; Abou Karaki, et al., 1993 (see figure 2.4). Figure from Al-Qaryouti (2002).

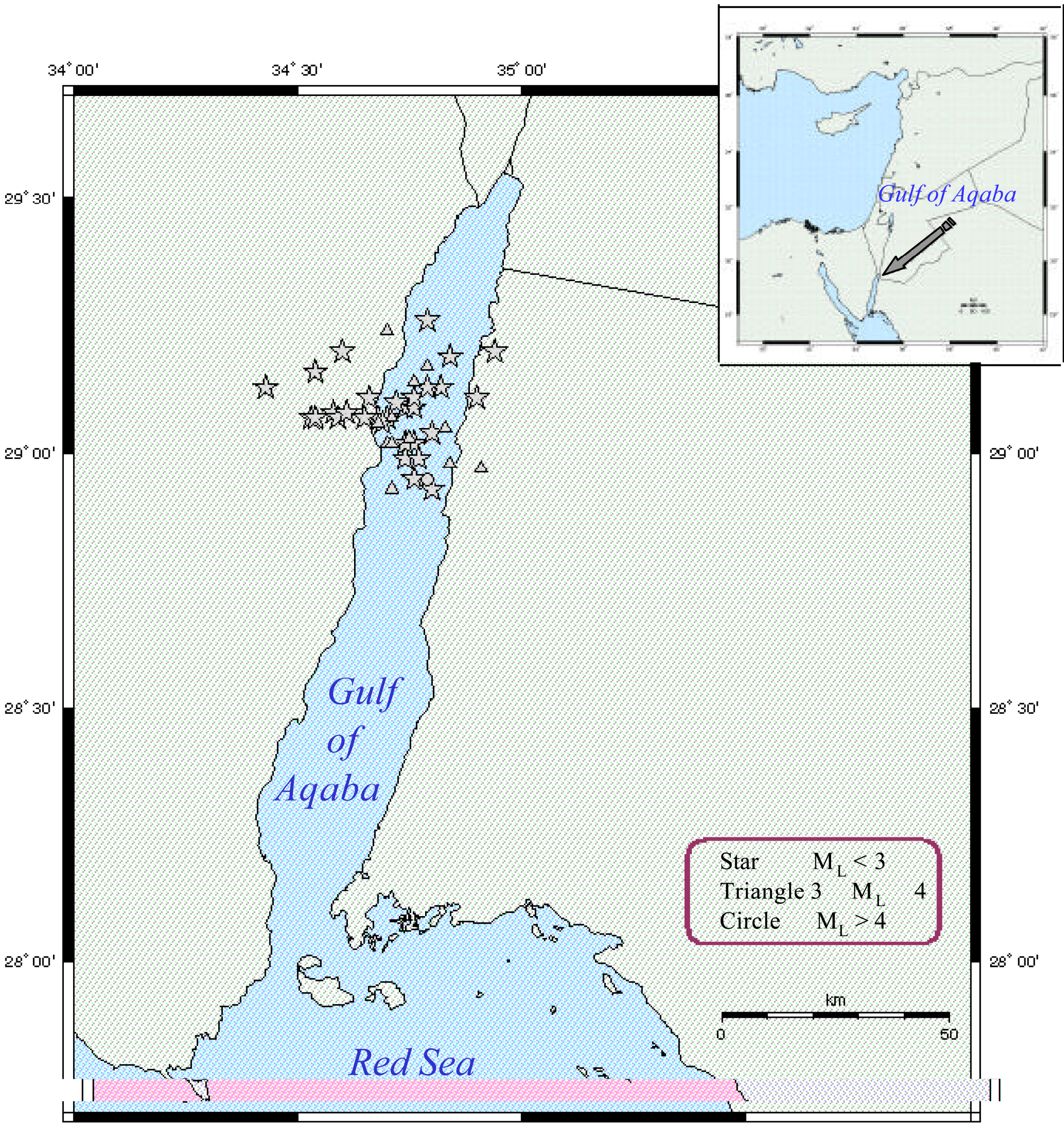


Figure 3.5: Location of earthquakes of 1990 earthquake swarm (Al-Qaryouti, 2002). Data from IPRG (1990).

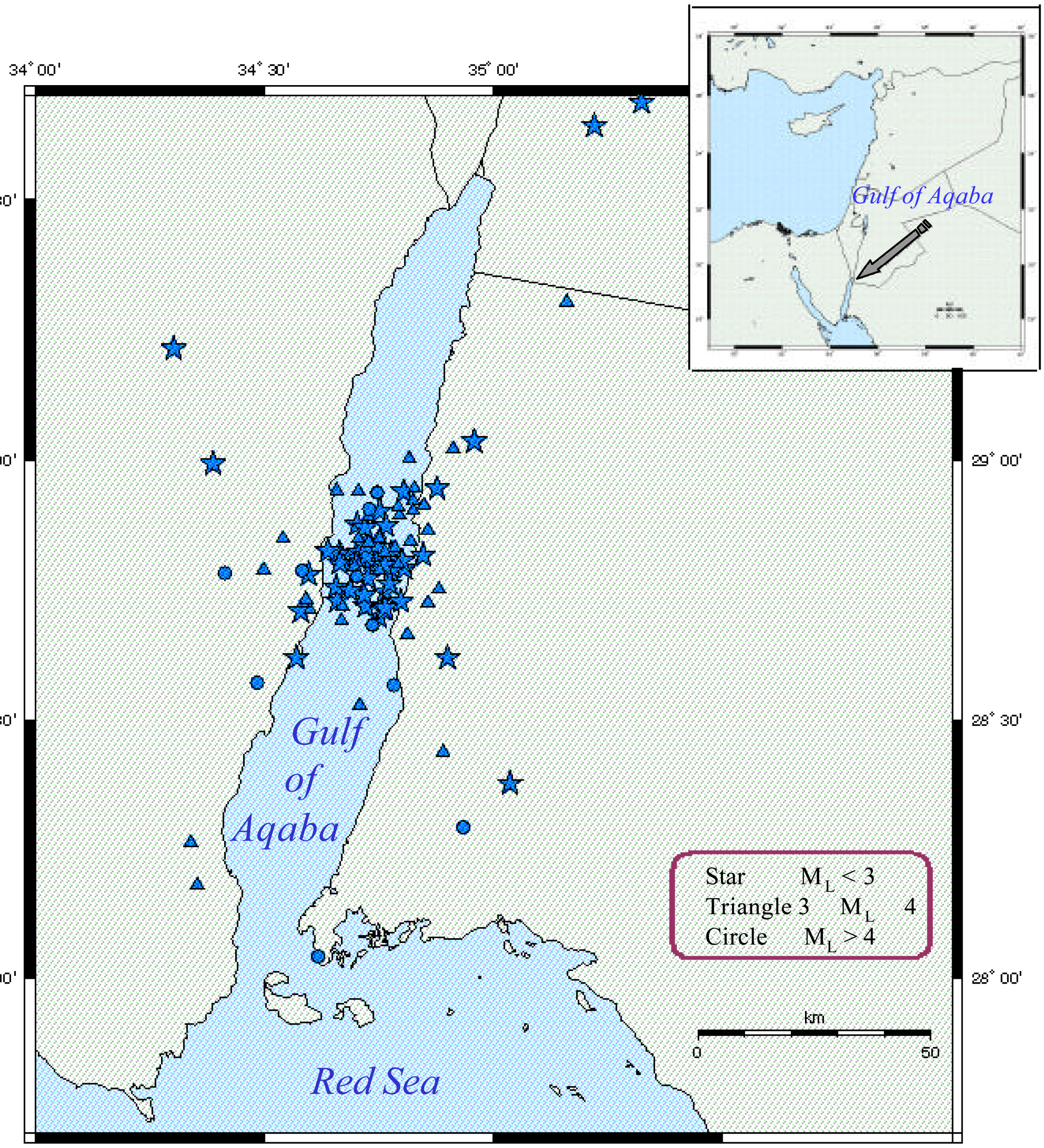


Figure 3.6: Location of earthquakes of 1993 earthquake swarm (Al-Qaryouti, 2002). Data from IPRG (1993).

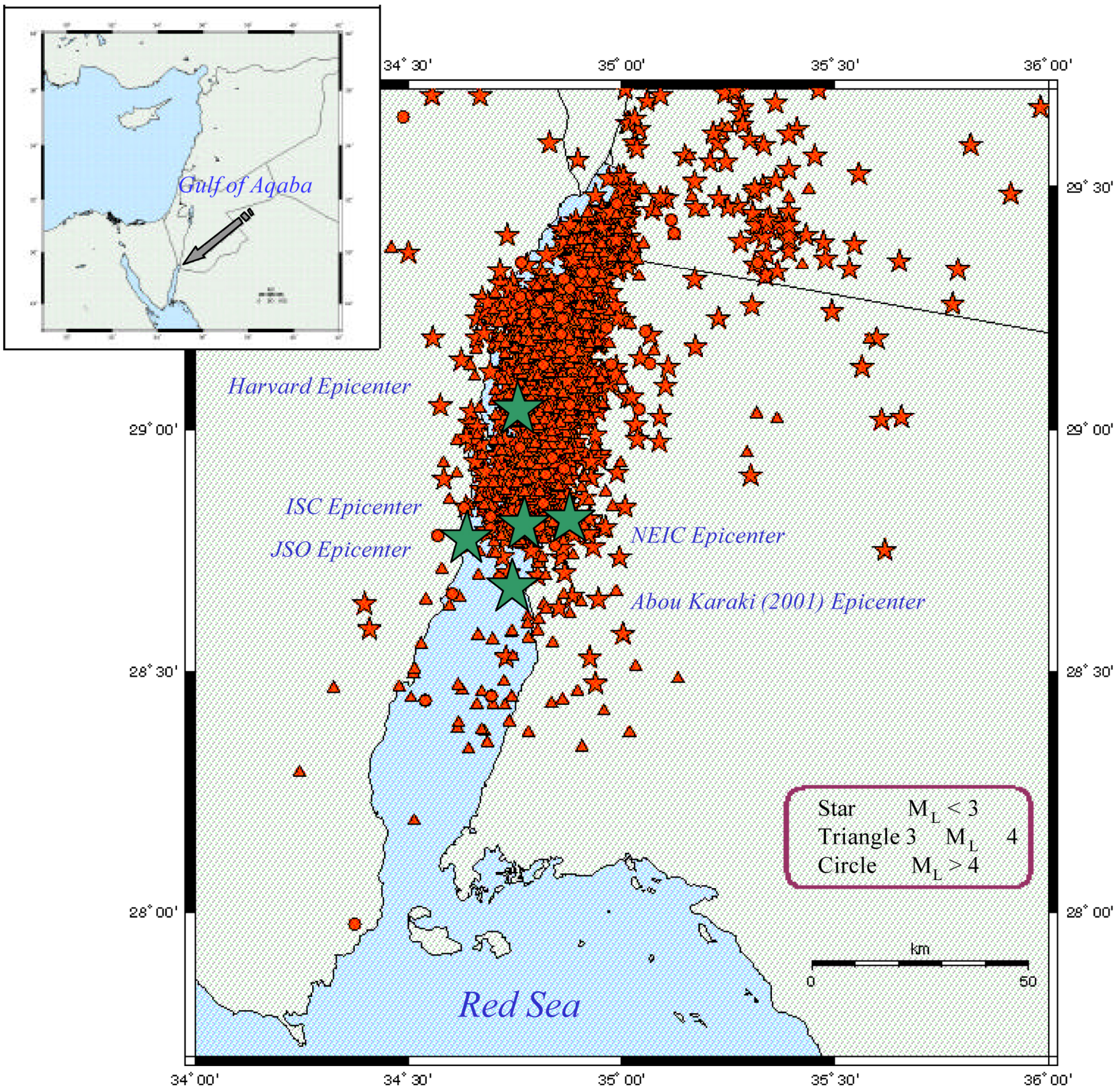


Figure 3.7: Location of earthquakes of 1995 earthquake swarm (Al-Qaryouti, 2002). Data from JSO (1995-1998).

Table 3.2: Statistics on the 1983, 1993, and 1995 Aqaba Gulf earthquake swarms (modified after Malkawi, et. al. 1999

Aspect	1983 swarms	1993 swarms	1995 swarms
Inception date	**21 January**	**3 August**	**22 November**
Duration (days)	**22**	**148**	**More than 6 months**
Total no. of events	**249**	**272**	**1236 until Dec. 31 1995**
Largest reported ML	**4.9**	**5.3**	**6.2**

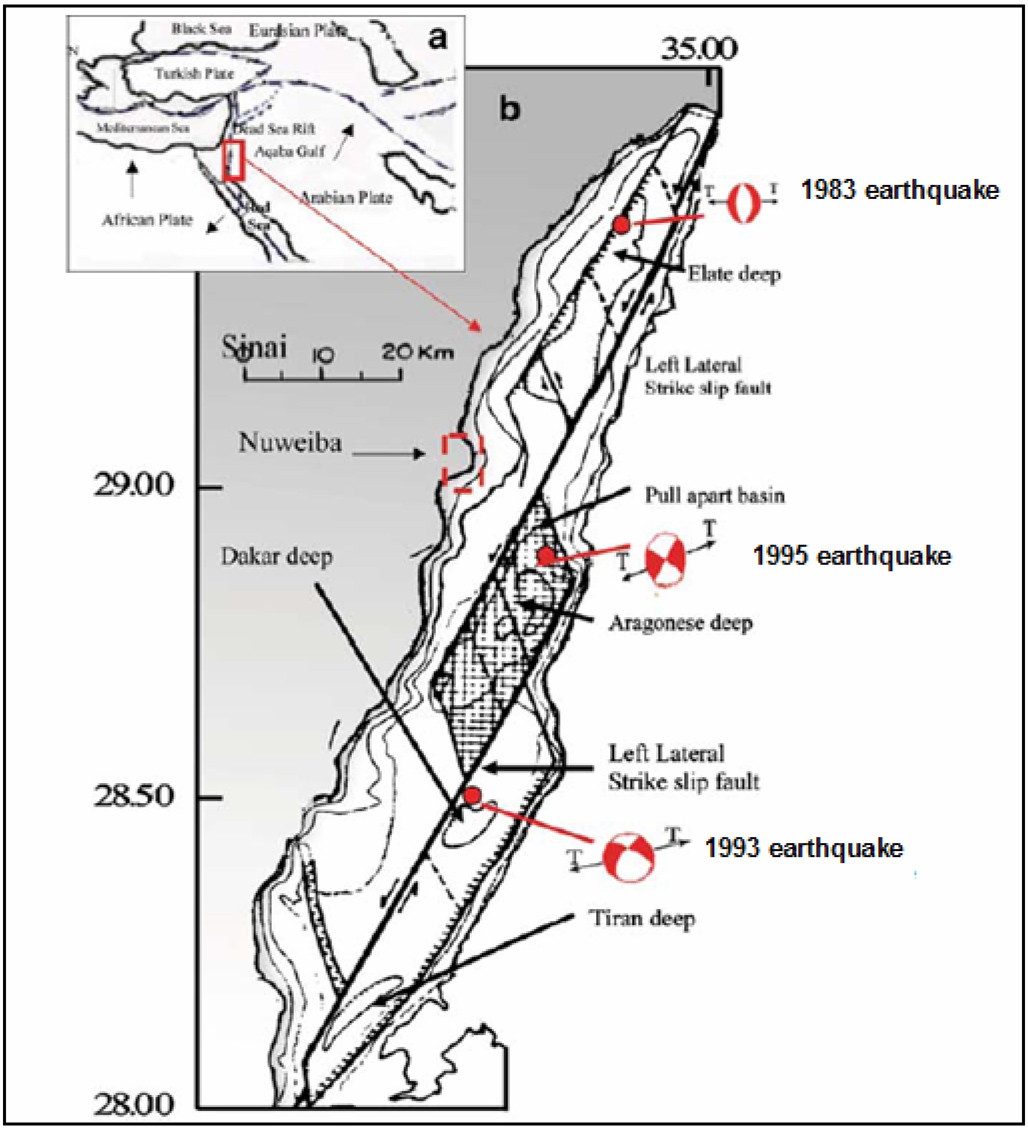


Figure3.8: The fault plane solution for 1983, 1993 and 1995 earthquakes. (After Ben-Avraham 1985 and 1987).

3.4 Updated earthquake catalogue

The compilation of the historical earthquakes and instrumentally recorded earthquakes that occurred in Jordan and adjacent area for the time period 1-2010 AD was conducted utilizing all available catalogues, namely, Ben–Menahem,1979; Poirier and Taher,1980; Hasweh,1986; Abou Karaki,1987; Ambraseys and Melville,1989; Ambraseys and Barazangi,1989; Al–Tarazi,1992; Jaber,1994; and Ambraseys, et al., 1994. From bulletins published by international agencies like Jordan Seismological Observatory (JSO), Natural Resources Authority (NRA), Amman, Jordan, and the Institute for Petroleum Research and Geophysics (IPRG) in Holon.

The earthquake activity and seismic parameters in the DST region are reported in two regular bulletins prepared by Institute for Petroleum Research and Geophysics (IPRG) and Jordan Seismological Observatory (JSO). Both organizations send their monthly lists to the International Seismological Center (ISC) in England and the National Earthquake Information Service (NEIS) in U. S. A, and the European Mediterranean Seismological Centre CSEM-EMSC (http://www.orfeus-eu.org/Links/euromed.html).

An updated earthquake catalogue is compiled after checking the quality, authenticity of data source and it is used in the assessment of earthquake hazards in the region.

The compiled catalogue is characterized by the following points:

1. The catalogue contains the following information about the earthquakes listed in this catalogue: origin times in (GMT) and date, epicenters in geographical locations in degree, magnitude (ML) and focal depths in kilometers.

2. The catalogue contains the historical and instrumental data including main shock earthquakes used to assess the seismic hazard in Jordan Dead Sea and the foreshock and aftershock earthquakes are removed to achieve two conditions; the independency of the data and Poisson's distribution of the data. (See Appendix 1).
3. The magnitude (ML) of historical earthquakes ranged between 5.2 and 7.1.
4. The magnitude of main shock earthquakes ranged between 4 and 7.1 in the period 1900-2011.The earthquakes for magnitude less than 4 were not considered as significant from a seismic hazard point of view.
5. Most earthquakes occurred at depths never exceeding 40 km (see figure 3.9)

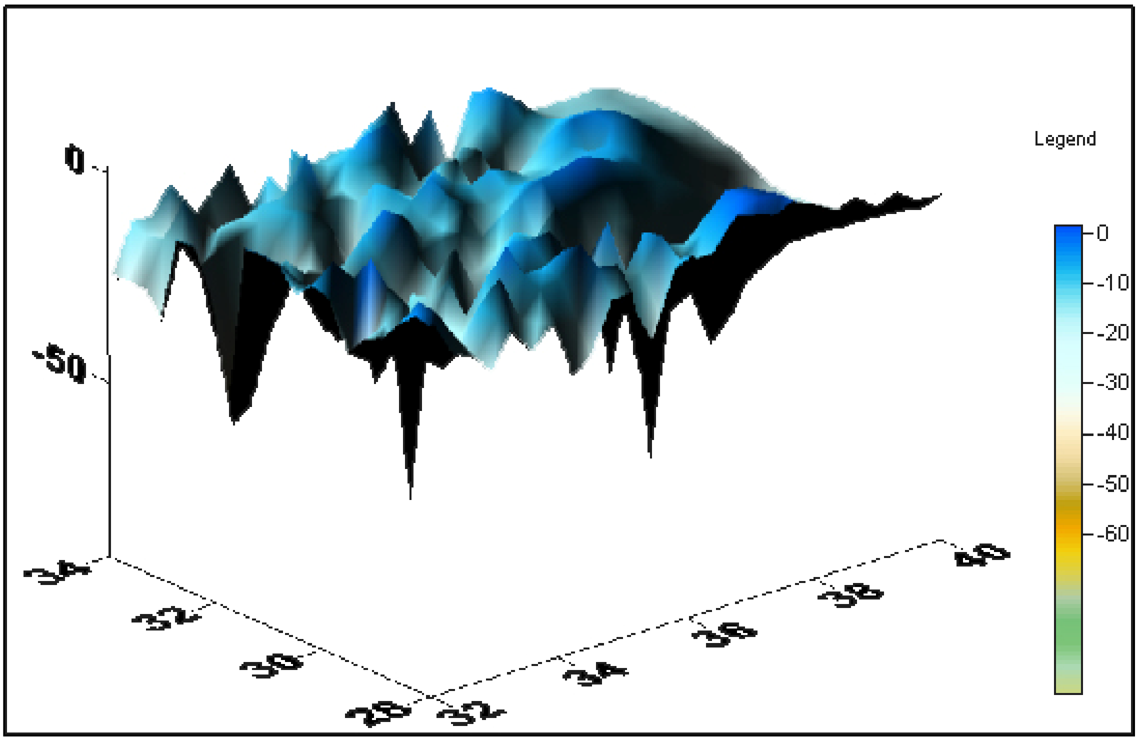


Figure 3.9: Focal depth (in km) distribution for the earthquakes in Jordan and surrounding area over the period 1900-2010.

In conclusion the seismicty in Jordan Dead Sea Transform is low to moderate according to instrumentally recorded earthquakes.

The instrumental seismicity of the region indicates that the Gulf of Aqaba has been the most the active segment of the plate boundary between the Arabian Plate and Sinai-Palestine Subplate from 1983 until now 2011.

CHAPTER 4

RELOCATION PROCESSING

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RELOCATION PROCESSING

4.1 Introduction

The relocation process was restricted to selected Gulf of Aqaba earthquakes located in JSO bulletins and for which we have complimentary available information from other sources ((Saudi Arabia (SNSN, King Abdulaziz City for Sci. and Tech) and Egypt, National Research Institute of Astronomy and Geophysics (NRIAG) Helwan)). Reliable location of local earthquakes is a function of data quality and location conditions, plus the adequate computer software, this includes the good azimuthal coverage of the network stations, and the realistic velocity models. It is possible to improve the accuracy of the hypocentral location process by considering the relocation parameters with care and by testing the crustal model for the region, choosing a better tested value of Vp/Vs ratio and testing the efficiency of stations involved in the relocation process.

In the following we discuss the details of the various steps performed to achieve better locations.

4.2 Seisan software

The "Seisan" software (developed by Department of Earth Science, University of Bergen) used in the relocation process is a complete set of programs and a simple data base for analyzing earthquakes from analog and digital data. With Seisan it is possible, using local earthquakes, to enter phase readings manually or pick them with a cursor, locate events, edit events, determine spectral parameters, seismic moment, azimuth of arrival from 3-component stations and plot epicenters (Havskov and Ottemöller, 2010)

The data is organized in a database like structure using the file system. The smallest basic unit is a file containing original phase readings (arrival times, amplitude, period, azimuth, and apparent velocity) for one event. The name of the file is also the event ID, which is the key to all information about the event in the database (Havskov and Ottemöller, 2010). For example, Poulsen and Simonsen(2006) used Seisan software for relocating earthquakes in Greenland region.

The programs are mostly written in Fortran and first developed for the VAX computer in 1988. In 1990 it was adapted to the Sun and PC environments. The programs have been compiled and linked with system compilers and linkers on SUN, GNU compiler on Linux and Digital Visual Fortran 5.0 under Windows. No format conversion is needed to move data files (binary and ASCII) between the systems. The SEISAN system is built of programs made by many different individuals (Havskov and Ottemöller, 2010).

The following steps describe in general how to use the program for locating the earthquake events:

1- Generate the input file which includes the date and the time of the event, the stations that recorded it, and the arrival time for P- wave and S-wave.

2- Applying different proposed constants (the value of Vp/Vs and the crustal model) requested by the software (to the whole sample).

3- After choosing the most suitable constants, the final results displayed by the program showing the location and the RMS of the results (figure 4.1).

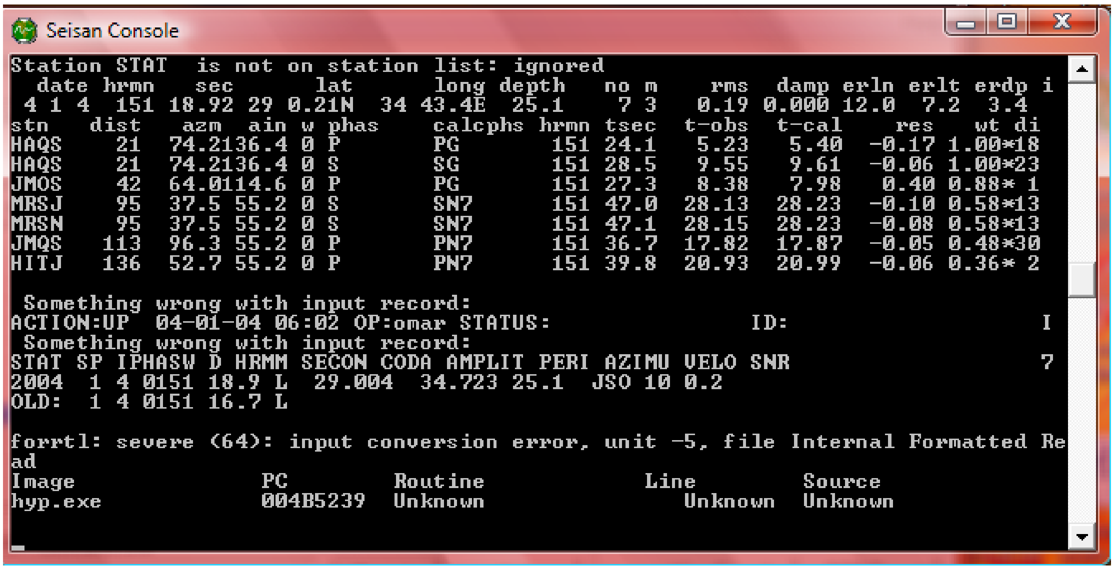


Figure 4.1: Selected earthquake event (4-1-2004) for the display of the final result for it.

4.3 Crustal structure and the velocity model

Studying the crustal structure for any region is a necessary step for improving the understanding of the tectonic setting and geodynamics of any region and most importantly this constitutes one of the main conditions towards a successful location of earthquakes.

The type of crust in the Red Sea changes gradually from continental to oceanic, from north to south. The Red Sea hills show by far the largest crustal thickness in the Red Sea environment of 32 km (Saleh, et al., 2006).

Drake and Girdler (1964) and Tramontini and Davies (1969) indicated that the recorded seismic velocities for p-waves are 5.8–5.9 km/s for the upper crust in the northern Red Sea, and the crust appears to be somewhat inhomogeneous in this area. Also, it was stated that the northern part of the Red Sea appears to be characterized by oceanic type crust, lying at a mean depth of 7–8 km, whereas the Moho is at a mean depth of 10–13 km (Gaulier, et al., 1988; Makris, et al., 1991; Rihm, et al., 1991).

The crustal structure on both sides of the Jordan-Dead Sea area have been studied through two deep seismic sounding experiments. The first was carried out in 1977, it was conducted in the Sinai plate (Ginzburg, et al., 1979, 1981), and the second was conducted in 1984 on the eastern flank of the DST (El-Isa, et al., 1987).

The 1977 experiment of deep seismic sounding was interpreted to show 35 km thickness of continental crust along the transform with thinning southwards to about 27 km south of Elat (Ginzburg, et al., 1981). The crust for the region between the Red Sea, Dead Sea and Mediterranean is about 40 km thick.

The results of the 1984 experiment show that much of Jordan is underlain by a continental crust and the thickness of the crust in the Aqaba region range between 32-35 km, and about 35 km in Amman area. In southeast Jordan the crust thickens to about 37 Km. Two transitional zones were recognized throughout the crust. The first zone between 18 and 20 km depth and separates between the upper crust with P-velocity in the range 5.8-6.5 km/s and the lower crust whose velocity is around 6.65 km/s. The other one occurs between the lower crust and the upper mantle with an average thickness of about 8 km (El-Isa, et al., 1987; Al-Qaryouti, 2002)

The crustal structure of the southern part of the Gulf is closer to the oceanic crust, but the central part of the Gulf of Aqaba is probably of transitional crustal structure (Ben-Avraham and Tibor, 1993).The northern part of the Gulf has continental crust structure. According to geophysical studies, Ben-Avraham (1997) suggested that the rifting activity propagates from the south northwards, and the mantle upwelling had probably took place in the southern and central part of the Gulf.

Shear velocity structure has been studied by (Corchete, at al., 2007) for the Sinai Peninsula. The obtained velocity models suggest the existence of lateral and vertical heterogeneity and its increase generally with depth for all paths analyzed in this area.

They found that the crustal thickness for the Gulf of Aqaba-Dead Sea region is about 30 km and the result was compared with results of Al-Amri and Alkhalifah (2004) who found the crustal thickness of Aqaba-Dead Sea region to be 28 km. Figure 4.2 shows a very similar trend, for both P and S velocity with depth between Corchete at al. (2007) model with the models obtained by Al-Amri and Alkhalifah (2004).

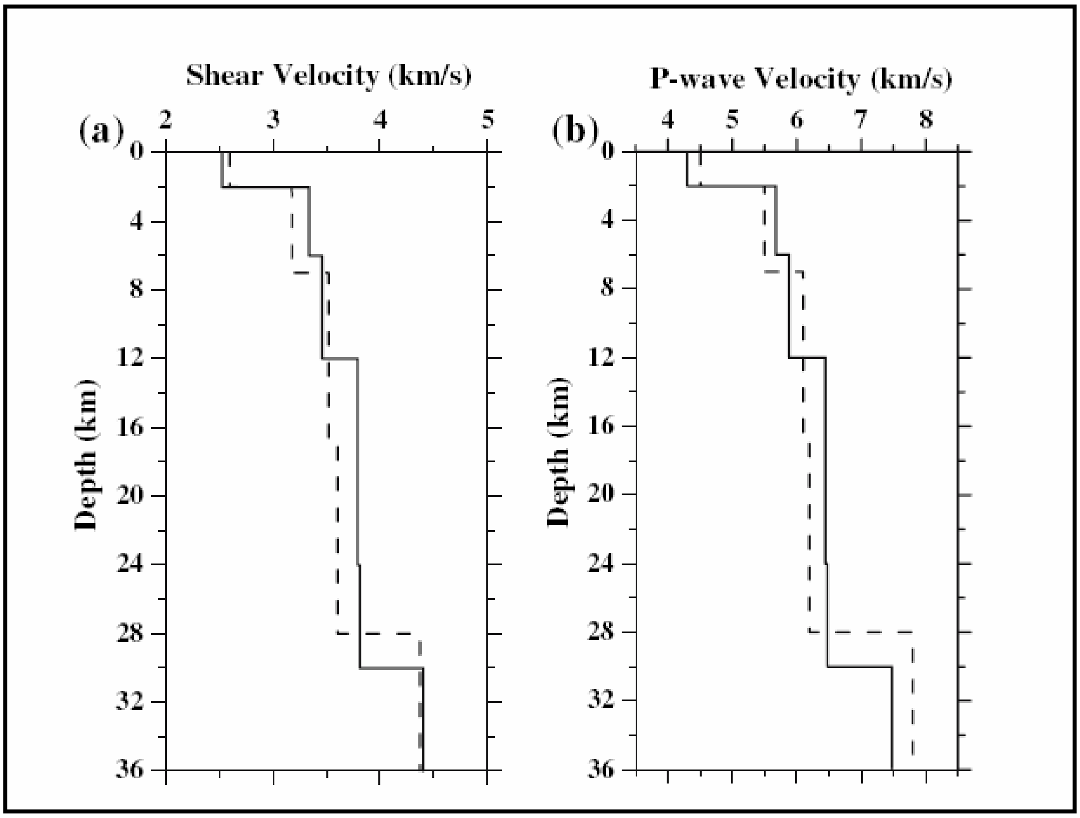


Figure 4.2: The trend of P and S velocity, velocity model obtained by Corchete, at al. (2007) plotted with continuous line, the model obtained by Al-Amri and Alkhalifah. (2004) is plotted with dashed line.

In this study 3 crustal models are tested to obtain the most suitable one for the location of earthquakes in the Gulf of Aqaba area. These models are listed in table 4.1. The average RMS error for each models are 0.21 for El-Isa, et al., (1986) model (see table 4.7), 0.26 for Abou Karaki (1987) model, and 0.32 for Al-Amri & Alkhalifah

(2004) model. The values for RMS which resulted from the use of Abou Karaki (1987) and Al-Amri & Alkhalifah (2004) models are shown in Appendix 2.

The most appropriate model for this study whish shows the minimum residual is the first one.

Table 4.1: The crustal models which tested in relocation process.

Model	**El-Isa, et al., (1986) model**		**Abou Karaki (1987) model**		**Al-Amri & Alkhalifah (2004) model**	
Layer parameters	H (km)	Vp (km/s)	H (km)	Vp (km/s)	H (km)	Vp (km/s)
First layer	1.5	3.50	2.5	3.50	2.0	4.50
Second layer	8.5	6.05	9.5	5.70	5.5	5.50
Third layer	8.0	6.32	8.0	6.10	20.5	6.00
Fourth layer	2.0	6.50	15	7.90		7.80
Fifth layer	8.5	6.65		8.10		
Sixth layer	5.0	7.38				
		8.10				

4.4 The Vp/Vs Value

In order to determine the value of Vp/Vs needed for relocation, Wadati technique diagrams and relations were followed, the resulting relation represents the Vp/Vs value as the slope of the best fit line drawn between the points represented by the relation between (tp) versus (ts - tp) + 1). 11 earthquakes recorded by JSO stations (table 4.2) and 4 recorded by Saudi stations (table 4.3) were used to determine this relation. The average value of Vp/Vs is 1.78. From table (4.2) and (4.3), there are generally quite small differences (Δ T) between the graphically deduced origin time using Wadati diagram (O.T*) and the origin time calculated using Seisan program (O.T), these results are within the reasonable acceptable limits.

Table 4.2: The Vp/Vs values for earthquakes recorded by JSO stations.

date	Latitude (N)	Longitude (E)	Vp\Vs	R^2	O.T	O.T*	Δ T
26/04/2000	29.956	34.424	1.841	0.99	01:03:28	01:03:29	+1
04/06/2001	28.814	34.819	1.827	0.99	18:02:38	18:02:40	+2
21/01/2004	29.790	34.671	1.868	0.97	02:42:52	02:43:01	-9
24/01/2004	29.261	34.880	1.699	0.99	15:51:04	15:51:03	-1
26/01/2004	29.267	34.852	1.880	0.99	12:25:49	12:25:56	+7
27/02/2004	29.182	34.854	1.655	0.99	22:39:20	22:39::21	+1
10-10 2004	30.149	35.234	1.810	0.97	21:05:18	21:05:20	+2
25/02/2002	27.524	34.831	1.810	0.98	07:25::01	07:25:21	+20
29/12/2002	29.187	34.705	1.770	0.98	11:33:19	11:33:26	+7
04/01/2004	28.903	34.799	1.730	0.94	01:51:17	01:51:29	+12
10/02/2004	29.180	34.869	1.680	0.99	21:10:21	21:10:26	+5

Table 4.3: Vp/Vs values for earthquakes recorded by Saudi Arabia stations.

date	Latitude	Longitude	vp\vs	R^2	O.T	O.T*	Δ T
21/01/2004	29.772	34.554	1.830	0.99	02:42:58	02:43:01	+3
27/02/2004	29.108	34.798	1.710	0.99	22:39:23	22:39:18	-5
10/02/2004	29.118	34.782	1.730	0.99	21:10:25	21:10:32	+7
10/02/2004	28.944	34.778	1.799	0.95	02:25:00	02:25:03	+3

Figures (4.3 – 4.16) show the slop of the best fit line drawn between the points represented by the relation between (tp) verses (ts - tp) + 1) to determine the Vp/Vs values. The cumulative relation between tp and ts-tp for all the events is shown in figure 4.17.

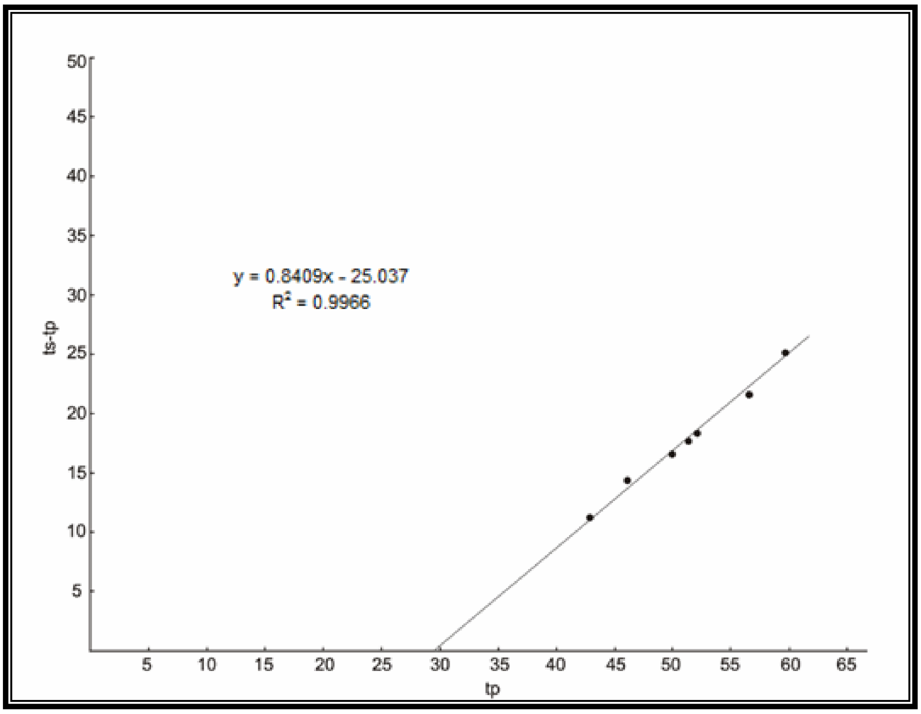


Figure 4.3: Relation between tp and ts-tp for 26/04/2000 earthquake using JSO data.

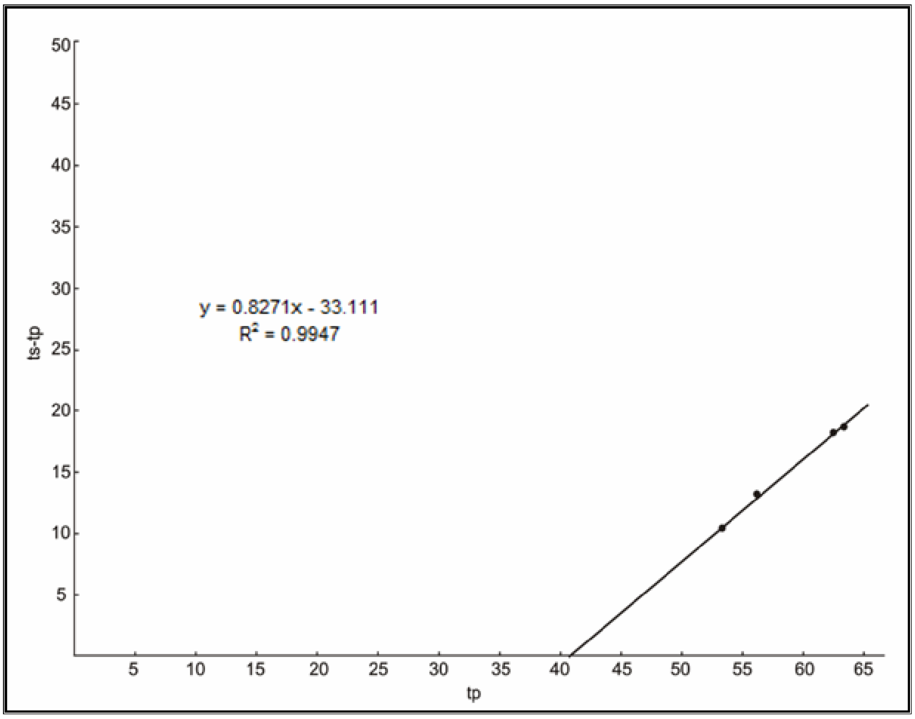


Figure 4.4: Relation between tp and ts-tp for 04/06/2001 earthquake using JSO data.

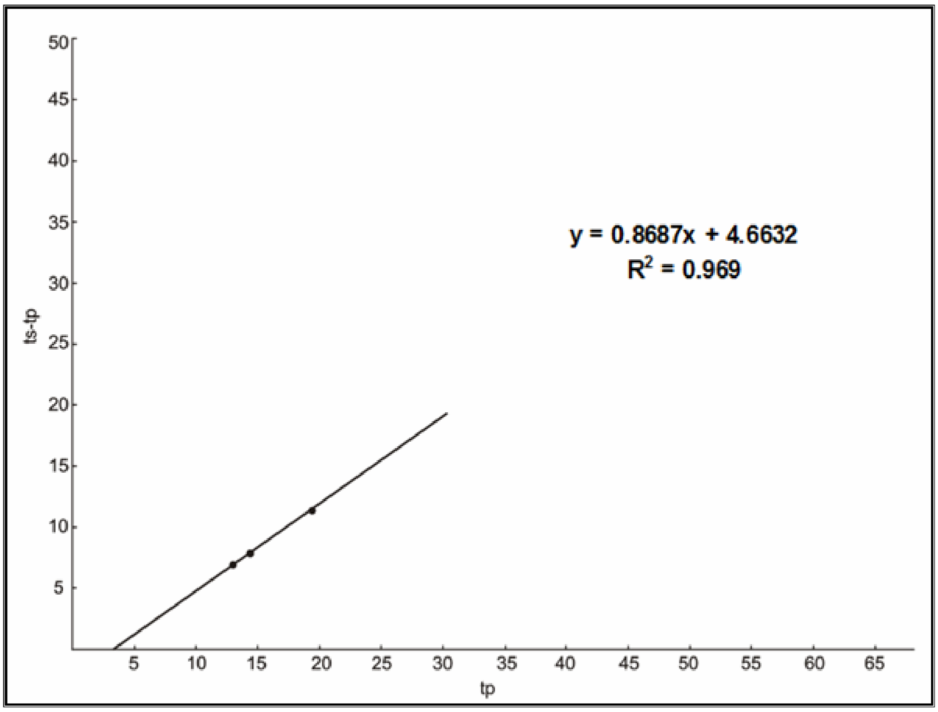


Figure 4.5: Relation between tp and ts-tp for 21/01/2004 earthquake using JSO data.

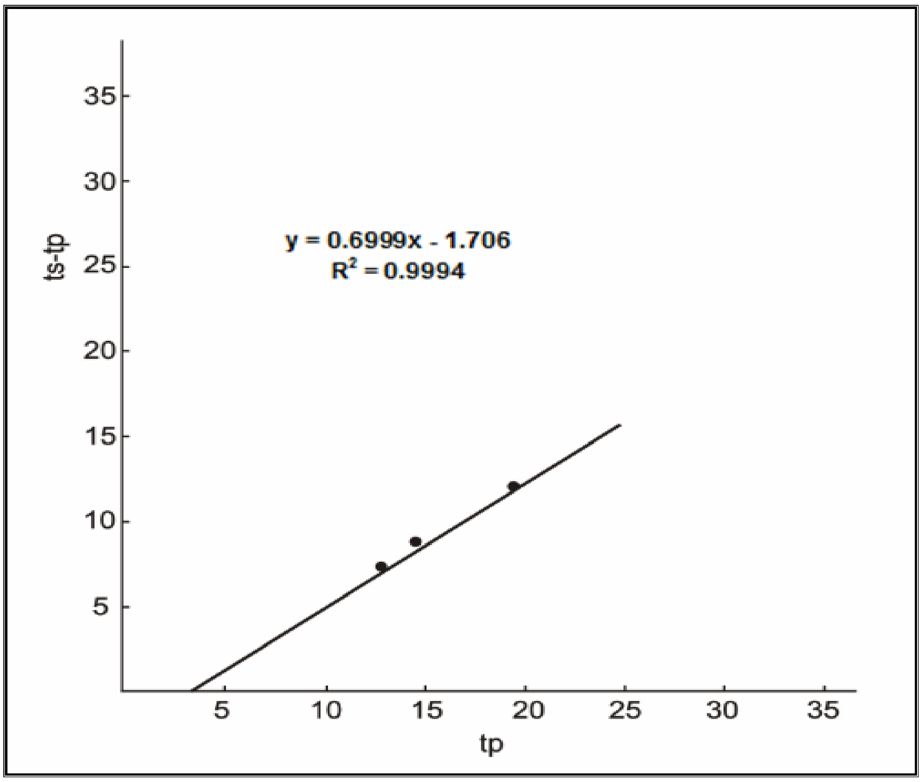


Figure 4.6: Relation between tp and ts-tp for 24/01/2004 earthquake using JSO data.

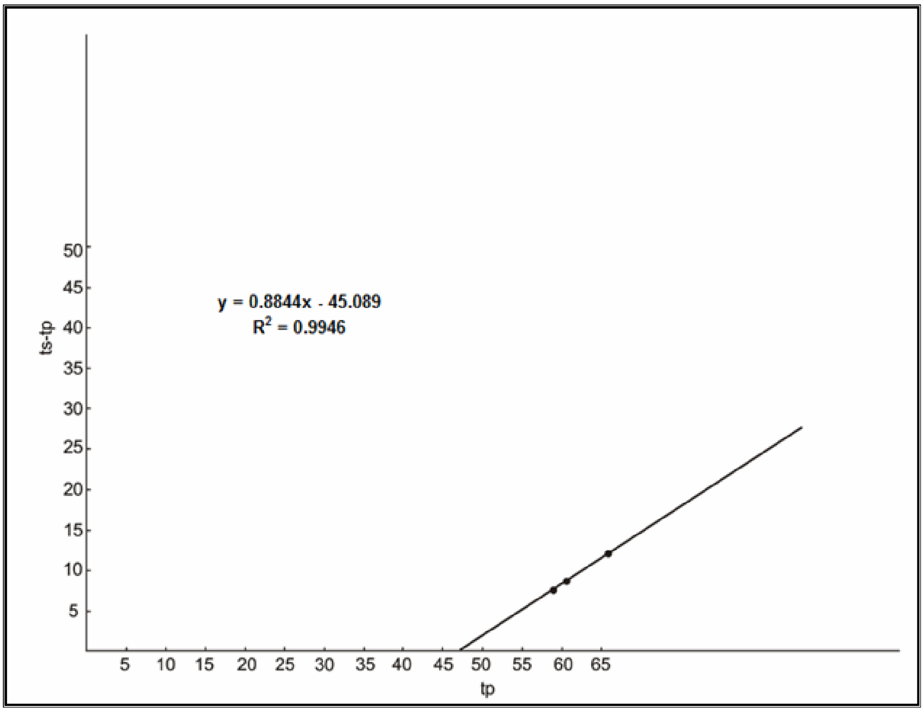


Figure 4.7: Relation between tp and ts-tp for 26/01/2004 earthquake using JSO data.

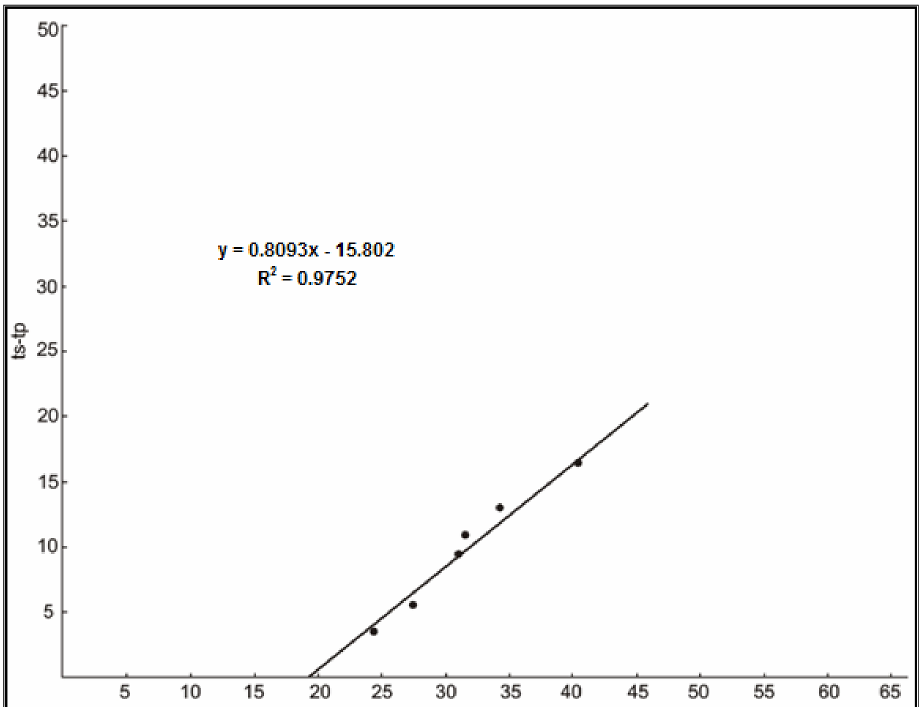


Figure 4.8: Relation between tp and ts-tp for 10-10 2004 earthquake using JSO data.

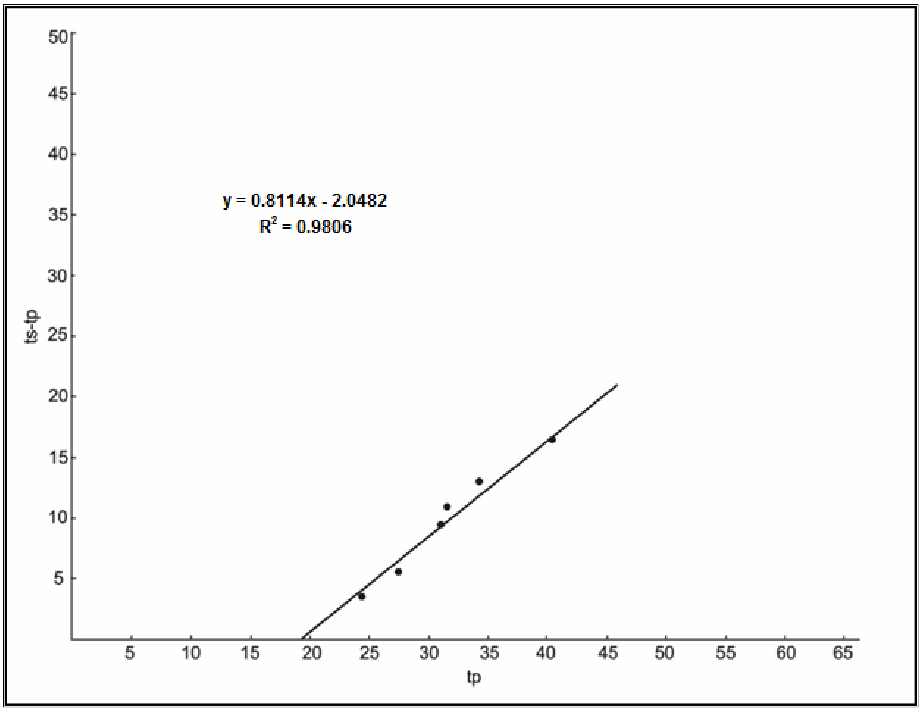


Figure 4.9: Relation between tp and ts-tp for 25/02/2002 earthquake using JSO data.

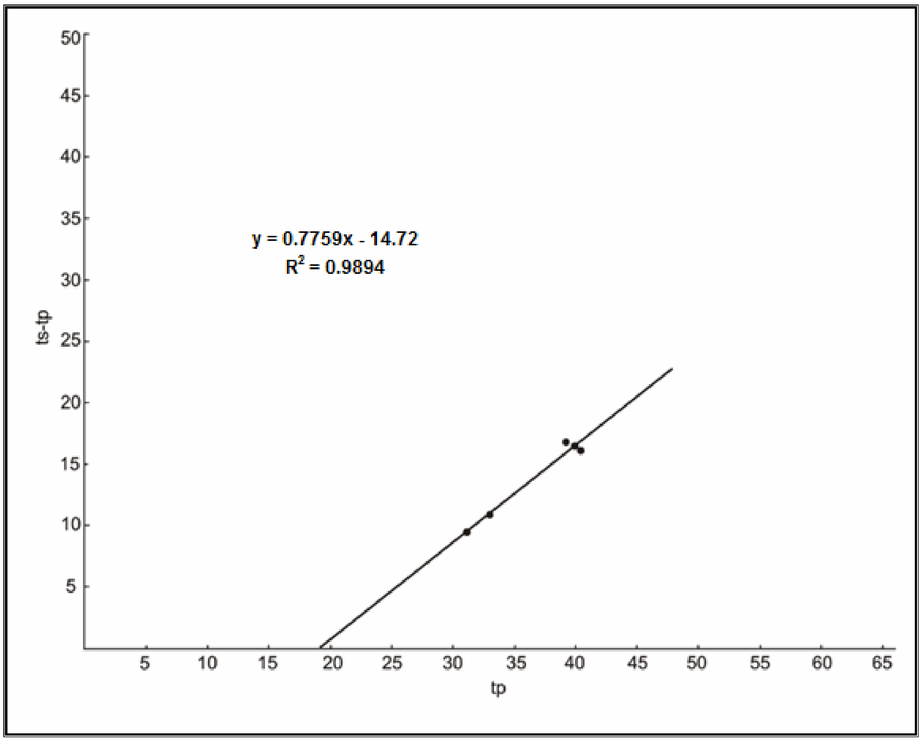


Figure 4.10: Relation between tp and ts-tp for 29/12/2002 earthquake using JSO data.

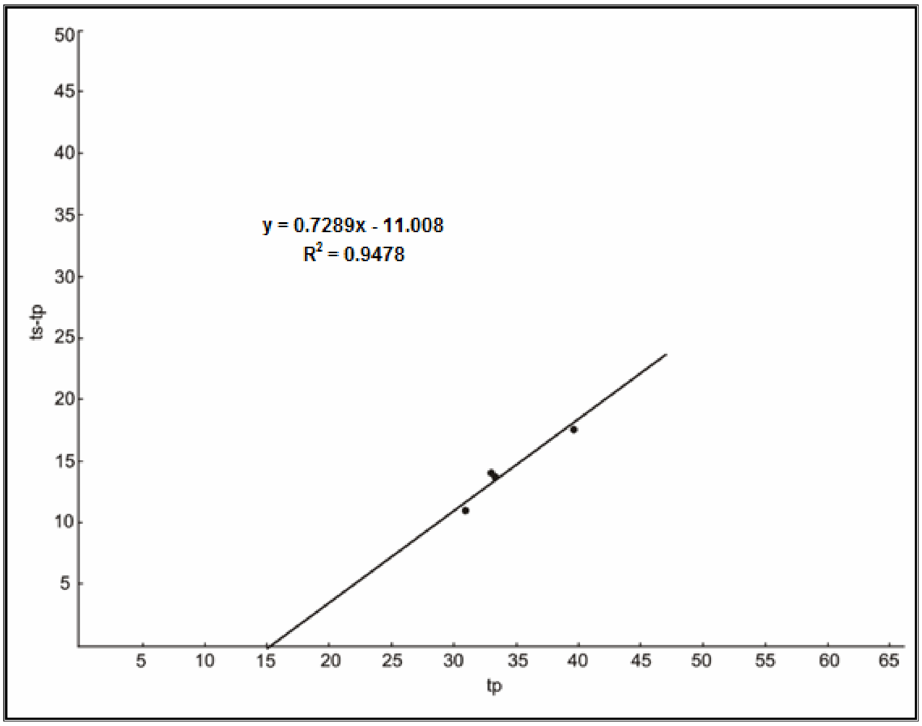


Figure 4.11: Relation between tp and ts-tp for 04/01/2004 earthquake using JSO data.

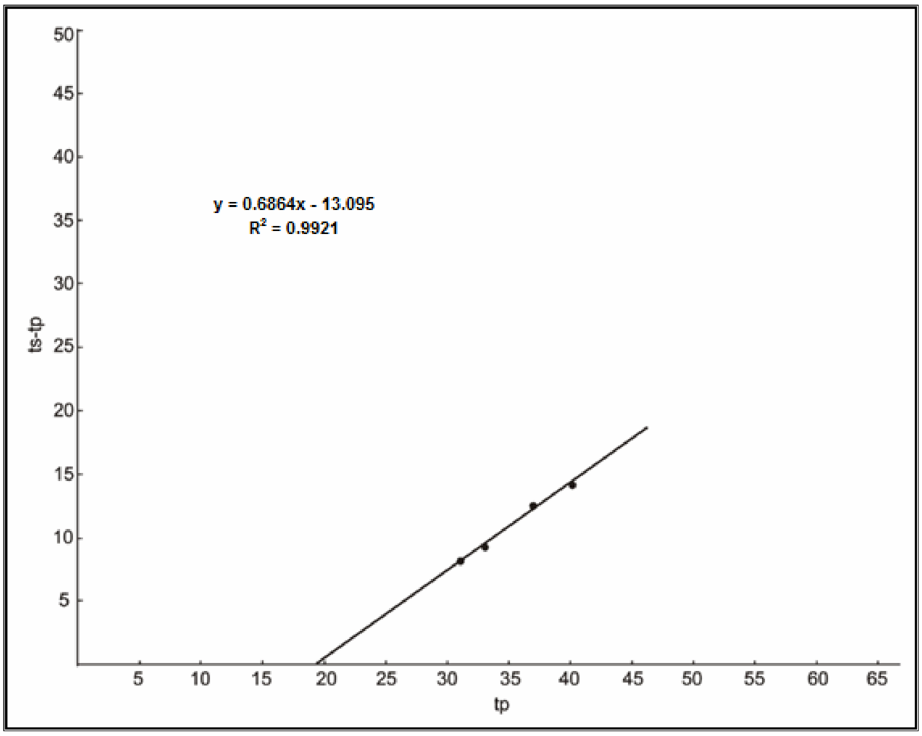


Figure 4.12: Relation between tp and ts-tp for 10/02/2004 earthquake using JSO data.

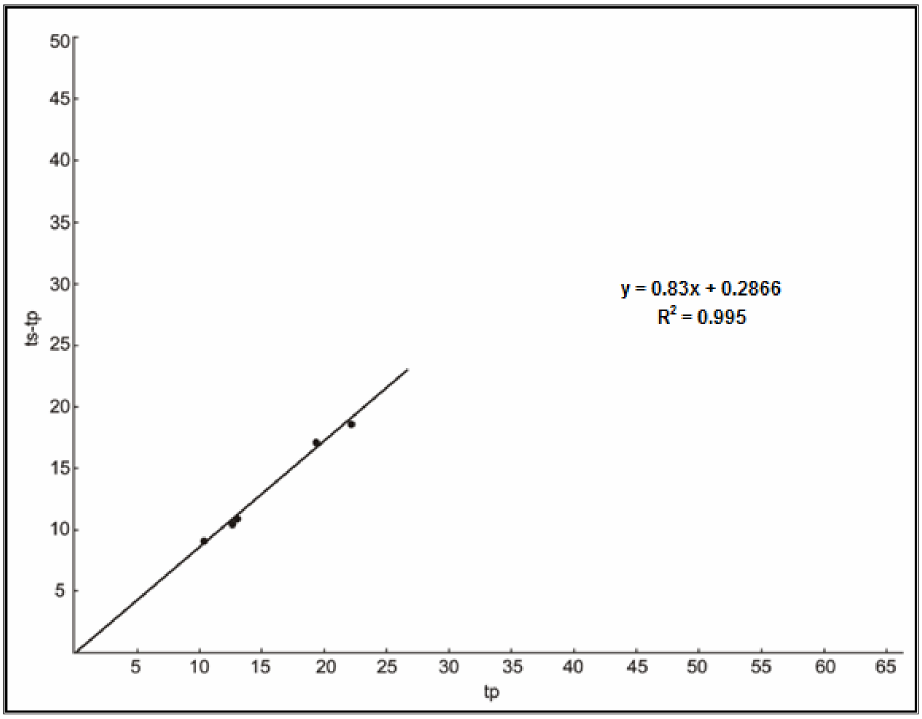


Figure 4.13: Relation between tp and ts-tp for 21/01/2004 earthquake using Saudi Arabia data.

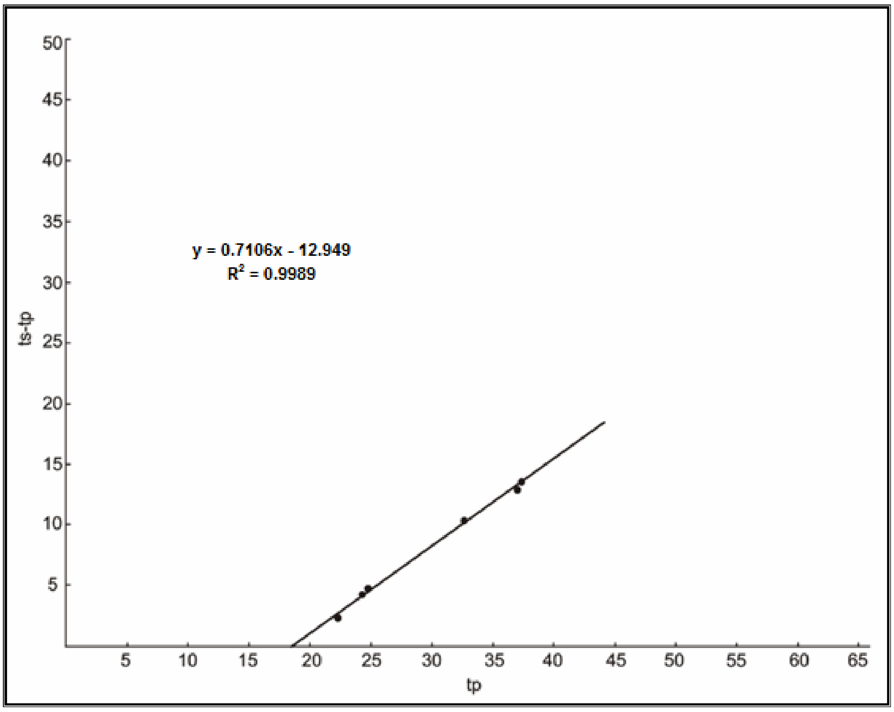


Figure 4.14: Relation between tp and ts-tp for 27/02/2004 earthquake using Saudi Arabia data.

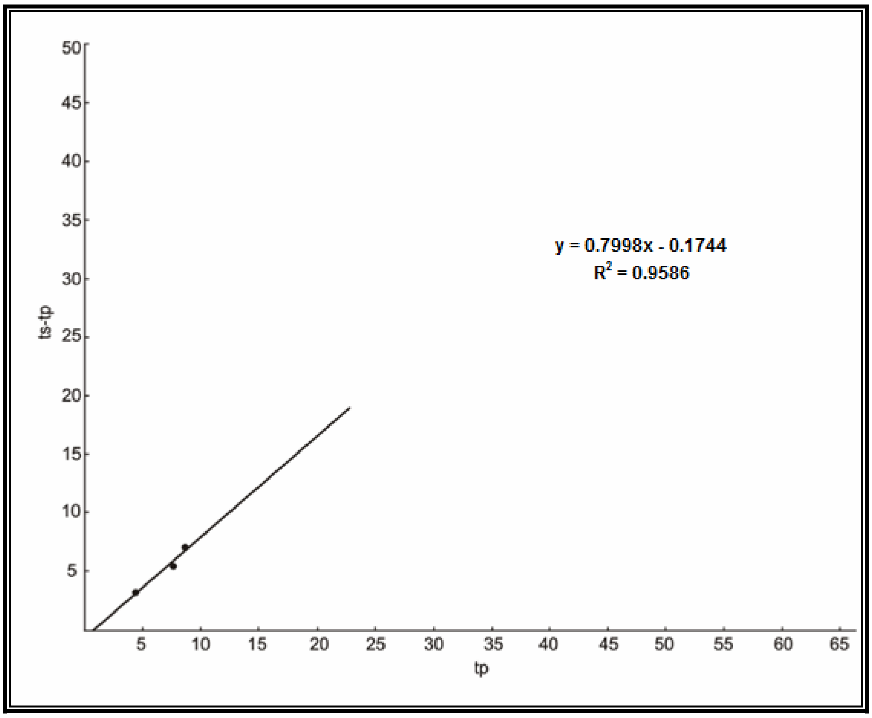


Figure 4.15: Relation between tp and ts-tp for 10/02/2004 earthquake using Saudi Arabia data (02:25:00).

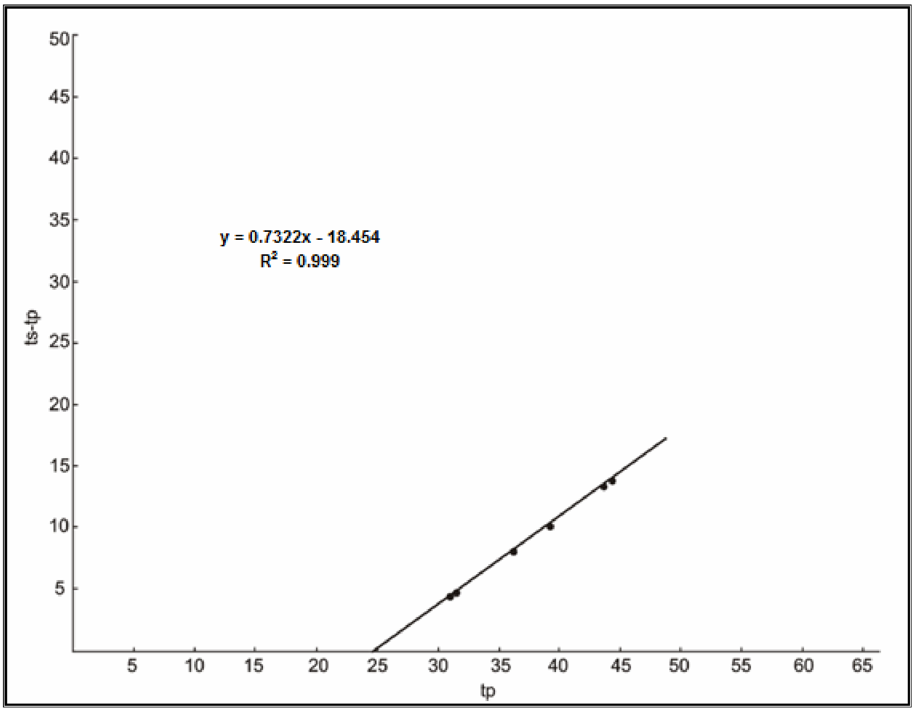


Figure 4.16: Relation between tp and ts-tp for 10/02/2004 earthquake using Saudi Arabia data (21:10:25).

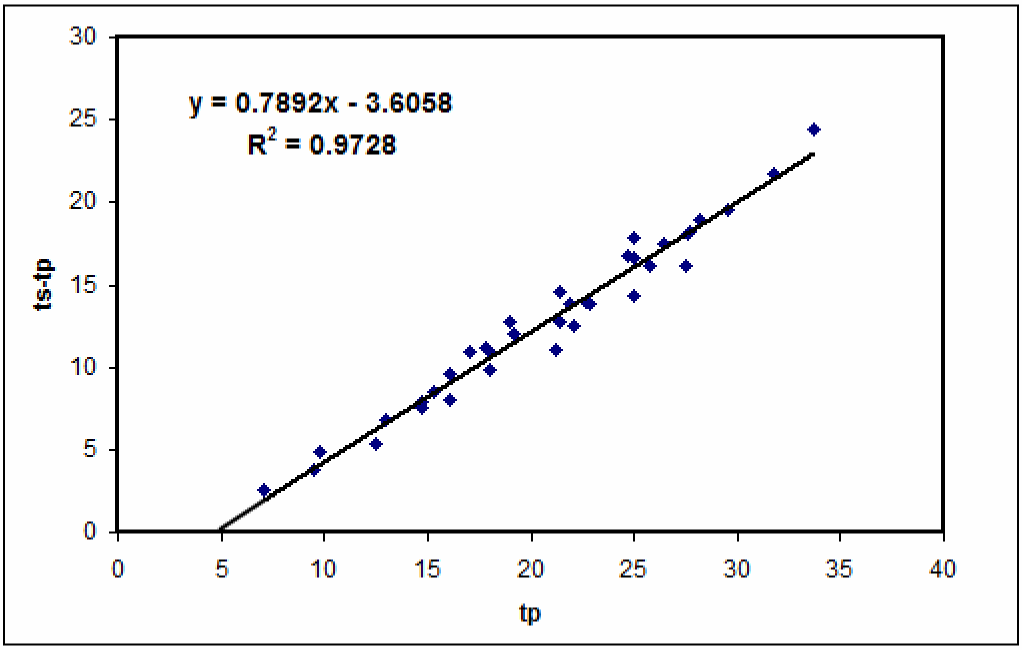


Figure 4.17: Cumulative relation between tp and ts-tp for all the events.

The cumulative relation between tp and ts-tp for all the events gives a vp/vs value which is almost similar to that obtained by computing the average vp/vs for the set of all individual events.

4.5 The efficiency of seismological stations used for relocation of earthquakes

The general methodology for testing the efficiency of seismological stations is based on analyzing the time residuals of arrival times for a sample of stations used in the location of earthquakes, the time residuals reflect the errors produced during the relocation process. These errors are either random or systematic or both as they may result from the inadequacy between the used crustal model and actual earth layers in the area or simply from personal or instrumental errors.

There are two indicators to help studying the "Efficiency of Seismological Stations" these indicators were introduced by (Abou Karaki, 1987, 1993, 2001), and the definition of these types is specified below:

1. Apparent Station Efficiency (ASE): it's the percentage of participation of a given station to the total number of events subjected to the study 'regardless of its resulting residuals.

2. Practical Station Efficiency (PSE): it's the percentage of acceptable contributions of the station in the location of the events (if it's residual did not exceed the limit that makes its data useful in the calculations). For example, European- Mediterranean Seismological Center, for its global locations of large earthquakes, removes any station having residuals exceeding 4 seconds as a result of availability of a large number of stations that spread over large areas for locating the earthquakes.

Eleven stations (table 4.4) were subjected to testing the efficiency by using 9 earthquakes, the information (for these earthquakes is summarized in table 4.5), since we are dealing with local events and a limited geographical area we have chosen the maximum Observed – calculated time limit that makes the station data useful to be 1 second.

Table 4.4: Stations subjected to testing efficiency.

No	Code	Name	Latitude (°)N	Longitude (°)E	Elevation (m)
1	NUB	(Egypt)	29.0270	33.9800	145
2	MRSJ	Marsad (Jordan)	29.6850	35.3220	810
3	TAYS	Tayyib Ism (Saudi Arabia)	28.5511	34.8717	303
4	BDAS	Al Bad (Saudi Arabia)	28.4317	35.1014	360
5	MDRJ	Muduarah (Jordan)	29.4420	35.8200	900
6	HITJ	Hittiya (Jordan)	29.7430	35.8410	1235
7	TR2	(Egypt)	28.3850	33.7220	275
8	JMQS	Jabal Moqyreh (Saudi Arabia)	28.8861	35.8778	1013
9	JMOS	Jabal al Moallq (Saudi Arabia)	29.1686	35.1094	870
10	ALWS	Ilw as Safayhah (Saudi Arabia)	29.3103	35.0650	585
11	HSHJ	Hashim (Jordan)	29.4210	35.4000	1100

Table 4.5: Information of 9 earthquakes employed in testing the efficiency of stations.

No	Date	Time	Lat	Long	Depth	Mag	RMS
1	09/01/2004	09:54:37	29.175	34.972	11	2.3	0.23
2	26/01/2004	12:25:57	29.347	35.113	16	2.0	0.30
3	10/02/2004	04:20:37	29.411	35.022	2	2.0	0.34
4	12/02/2004	1:04:54	29.235	34.83	16	2.1	0.19
5	15/02/2004	19:52:40	29.313	34.993	10	3.1	0.23
6	25/02/2004	04:38:10	29.324	35.133	20	2.6	0.36
7	25/02/2004	14:53:47	29.015	34.783	9	2.7	0.31
8	10/02/2004	21:10:23	29.228	34.95	17	2.3	0.37
9	10/02/2004	21:27:17	29.224	34.958	19	2.5	0.37

The results of testing the efficiency for the stations are shown in figures from (4.18 to 4.28), and summarized in table (4.6). All stations show quit acceptable results

except JMQS, JMOS and ALWS stations. As a result, data from these stations were excluded and were not used in the relocation of events.

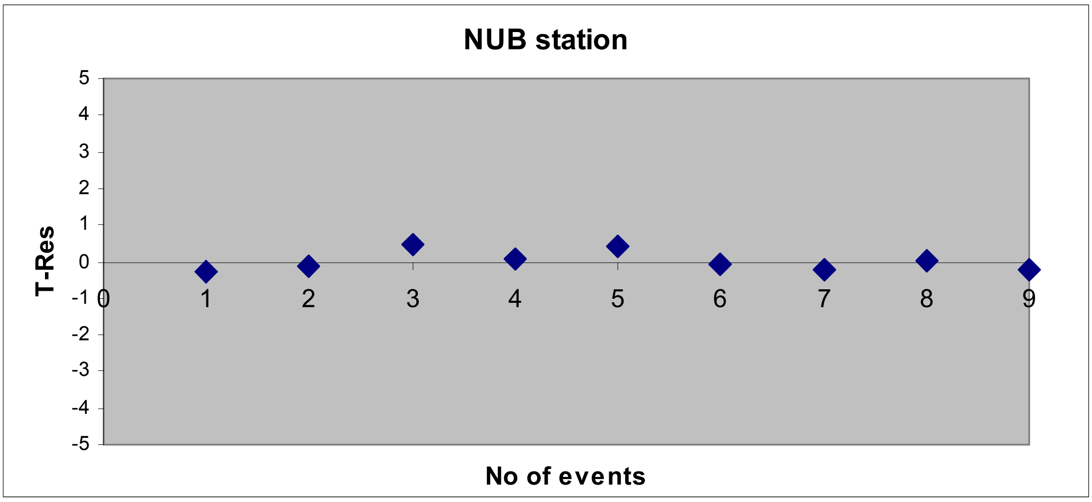


Figure 4.18: The efficiency of NUB station (PSA =100% and ASE= 100%).

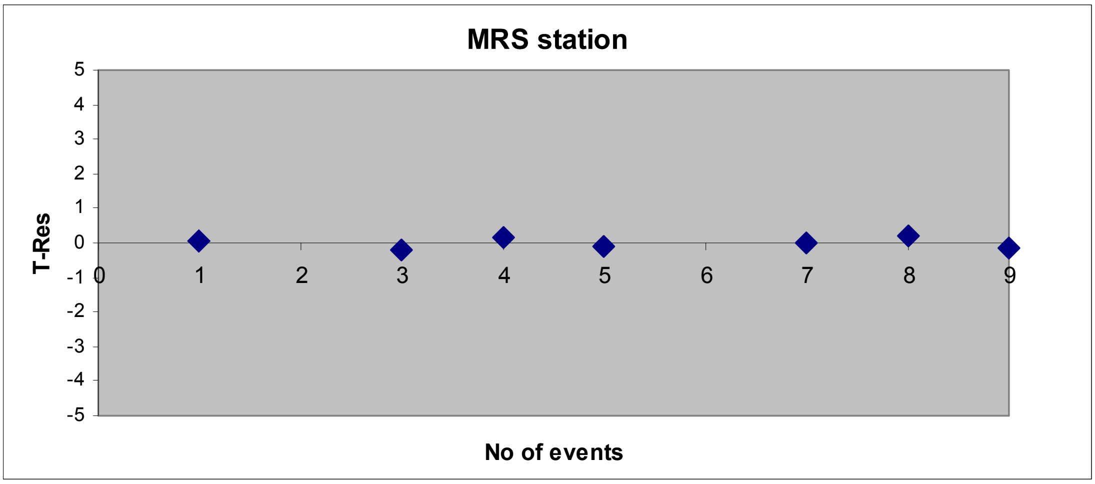


Figure 4.19: The efficiency of MRS station (PSA =100% and ASE= 78%).

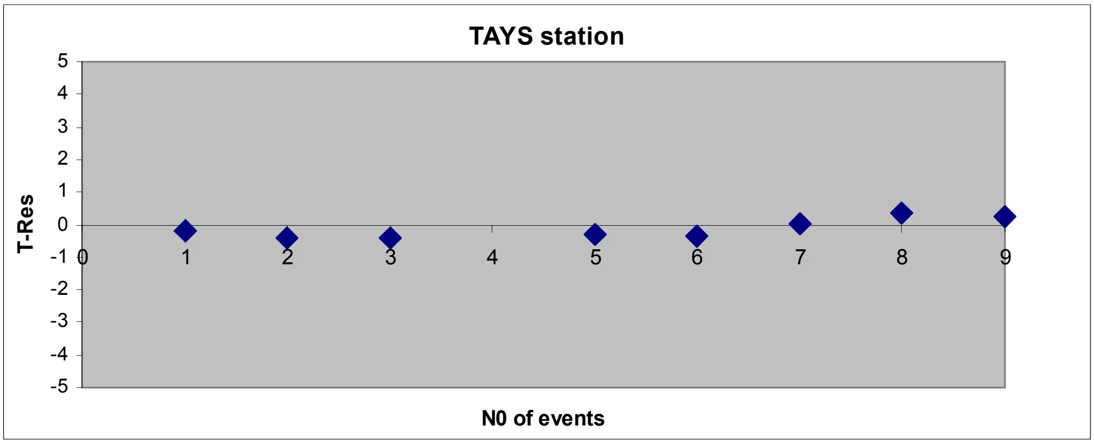


Figure 4.20: The efficiency of TAYS station (PSA =100% and ASE=89%).

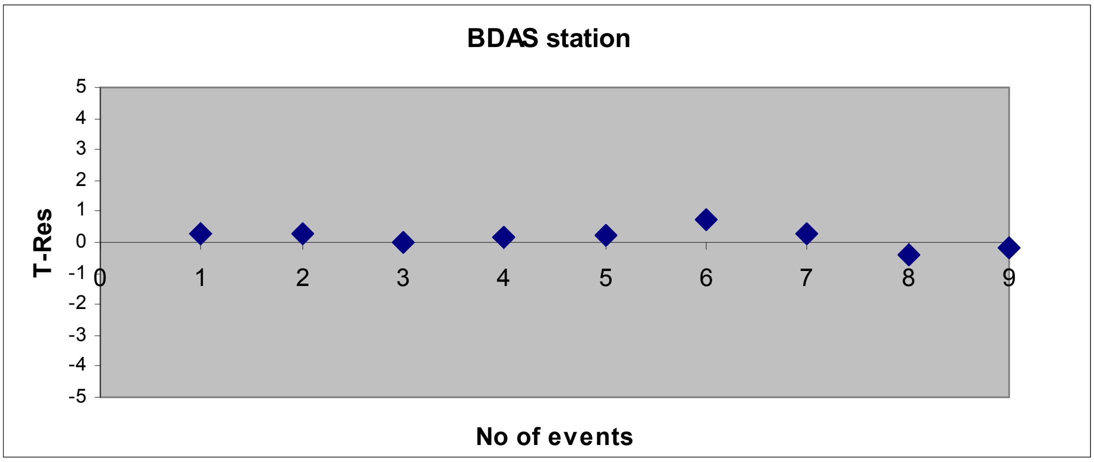


Figure 4.21: The efficiency of BDAS station (PSA =100% and ASE=100%).

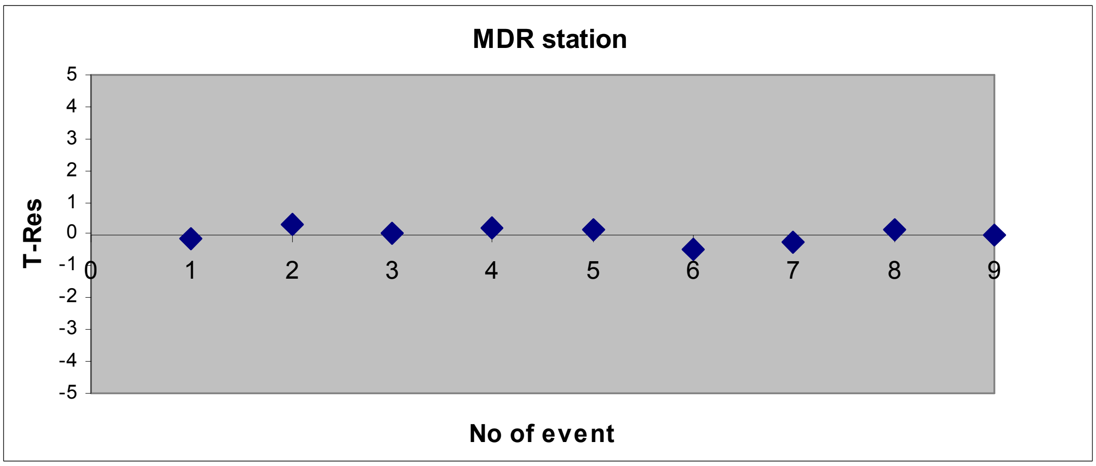


Figure 4.22: The efficiency of MDR station (PSA =100% and ASE= 100%).

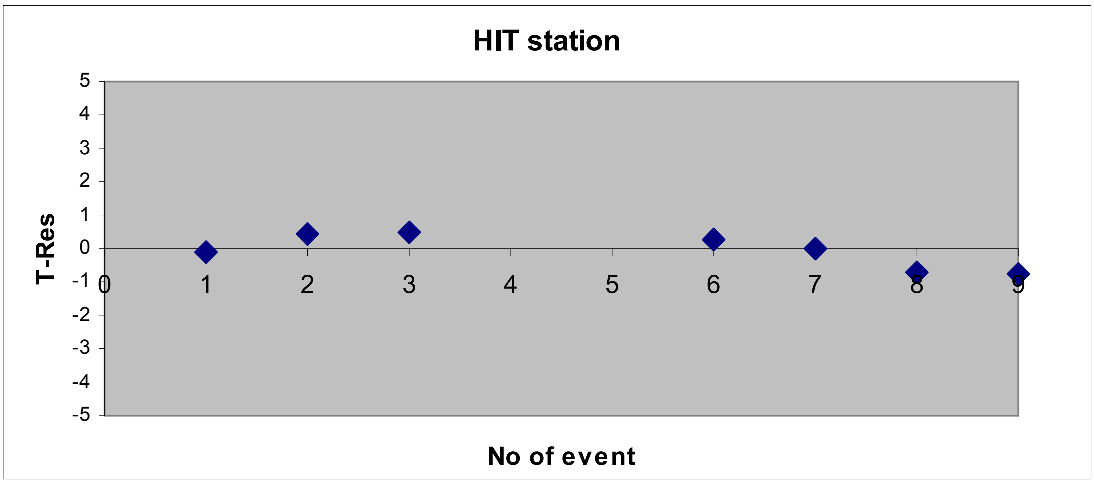


Figure 4.23: The efficiency of HIT station (PSA =100% and ASE= 78%).

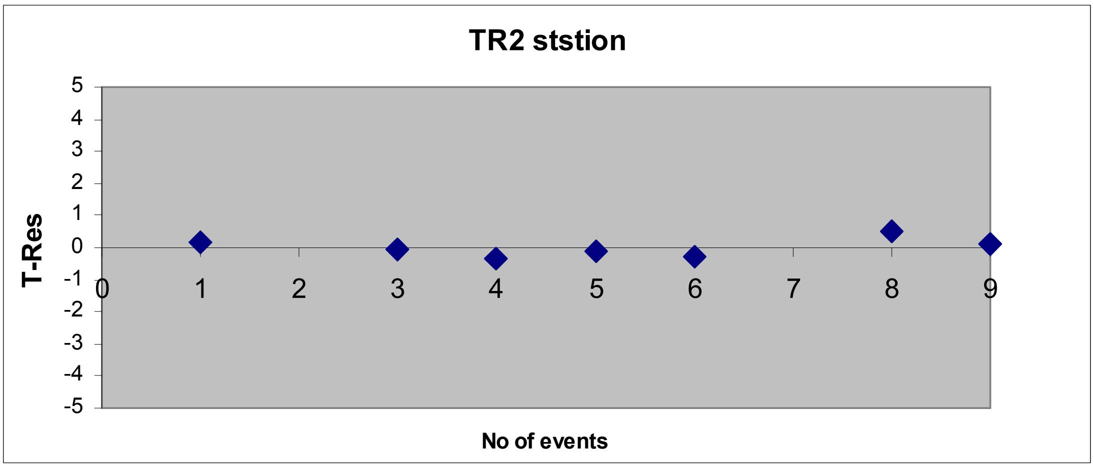


Figure 4.24: The efficiency of TR2 station (PSA =100% and ASE=78%).

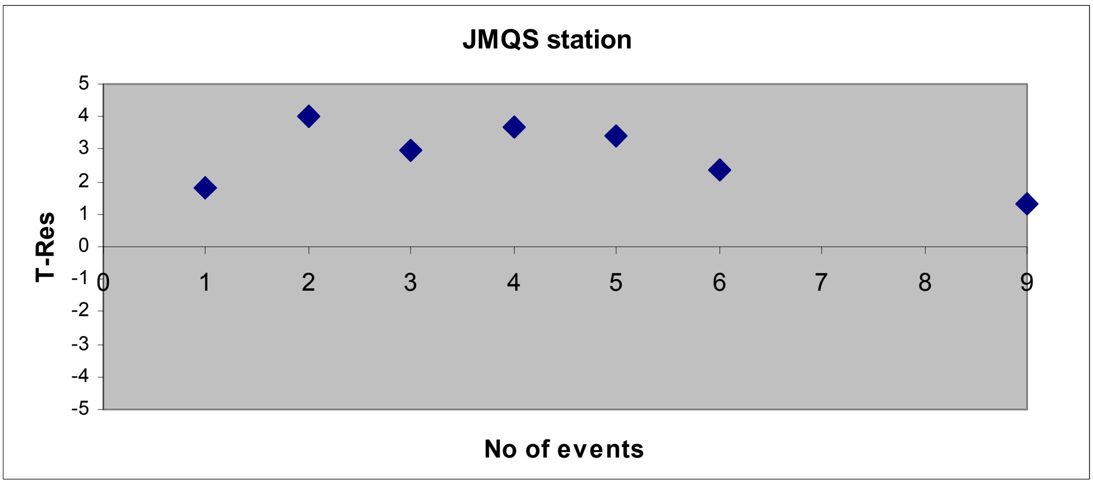


Figure 4.25: The efficiency of JMQS station (PSA =0% and ASE= 78%).

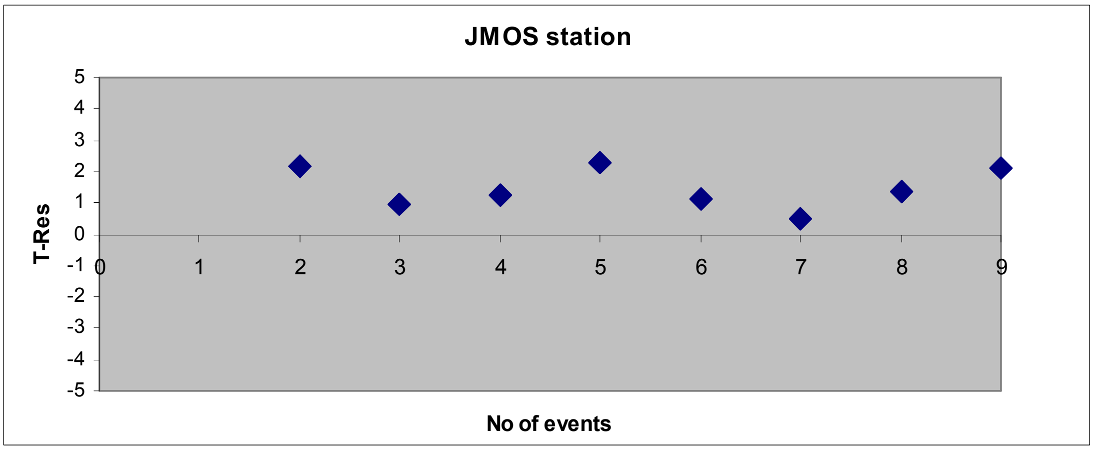


Figure 4.26: The efficiency of JMOS station (PSA =11% and ASE= 89%).

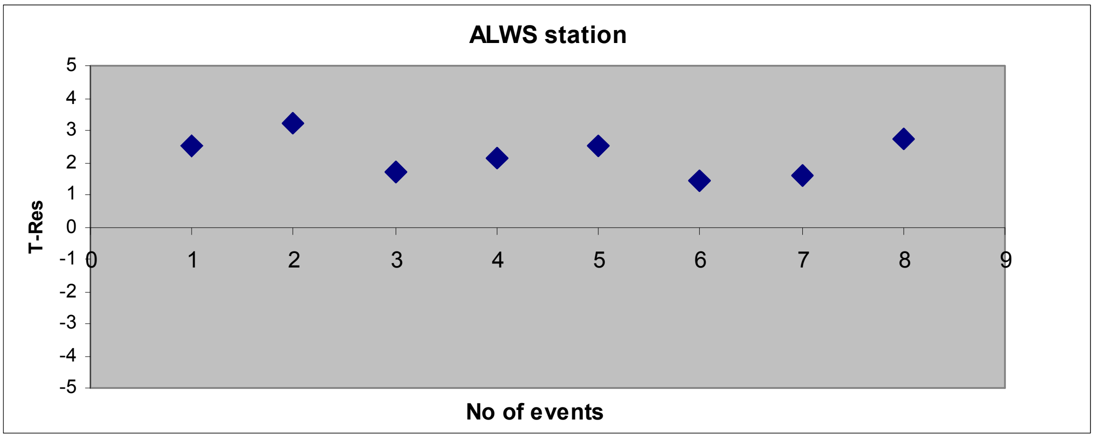


Figure 4.27: The efficiency of ALWS station (PSA =0% and ASE= 89%).

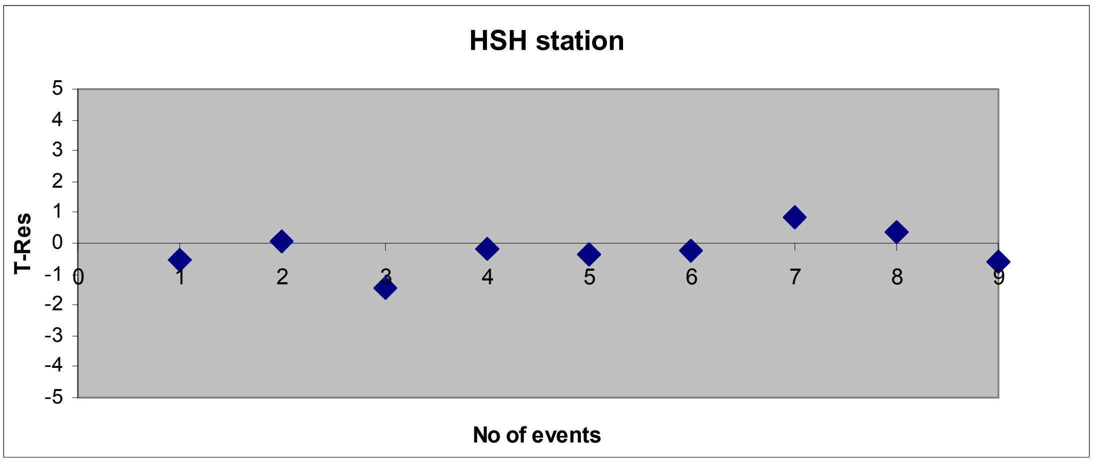


Figure 4.28: The efficiency of HSH station (PSA =78% and ASE=100%).

Table 4.6: The results for testing the efficiency for 11 stations.

Station name	PSA	ASE
NUB	100%	100%
MRS	100%	78%
TAYS	100%	89%
BDAS	100%	100%
MDR	100%	100%
HIT	100%	78%
TR2	100%	78%
JMQS	0%	78%
JMOS	11%	89%
ALWS	0%	89%
HSH	78%	100%

From figures (4.18-4.28) we can notice that The residuals of all stations are around zero and didn't exceed the maximum limit that makes the station data useful, but JMQS, JMOS and ALWS stations show that the residuals are over the maximum limit and all the residuals are positive and in the same trend (can be correlated), which means that there are systematic errors in data from these stations and these can be corrected (figure 4.29). These stations are located to the east of the epicentral distribution and within certain direction (figure 4.30), which means that the source of the errors may have resulted from inadequacies in the crustal model with respect to the position of these stations.

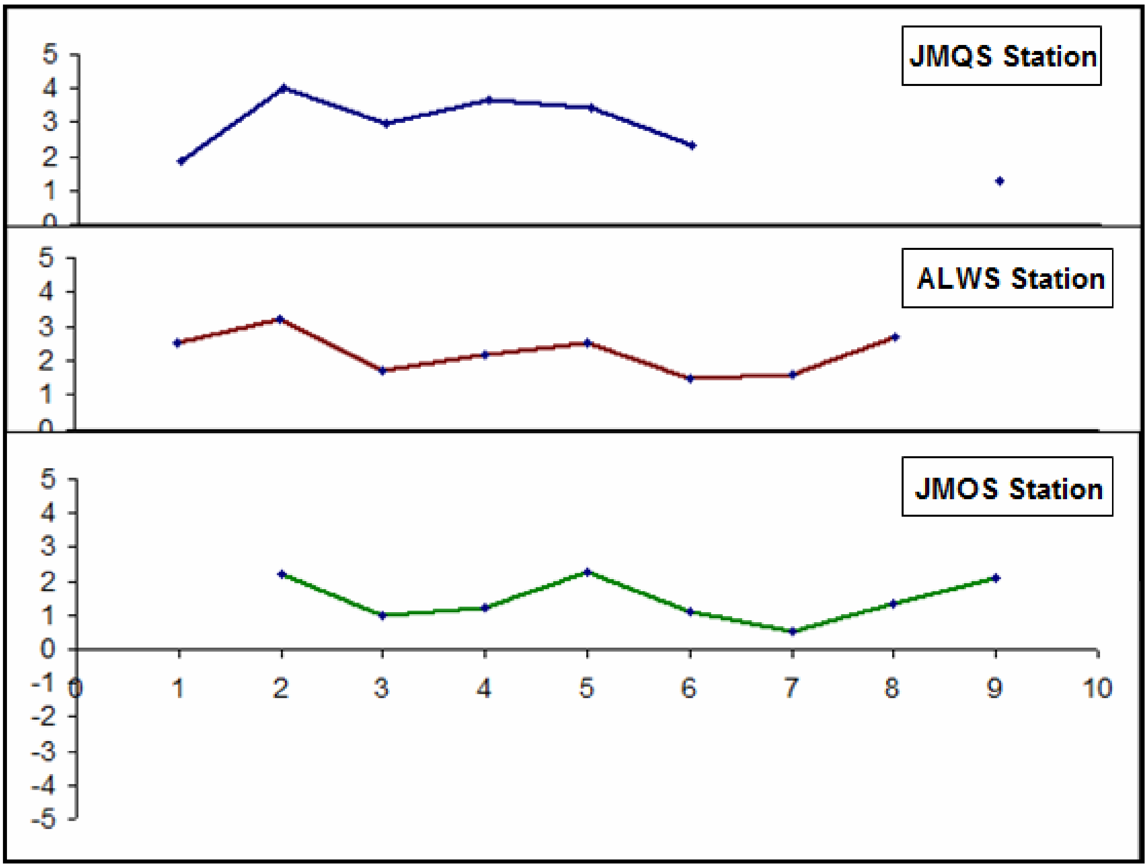


Figure 4.29: Trend of time residual for JMQS, JMOS and ALWS stations.

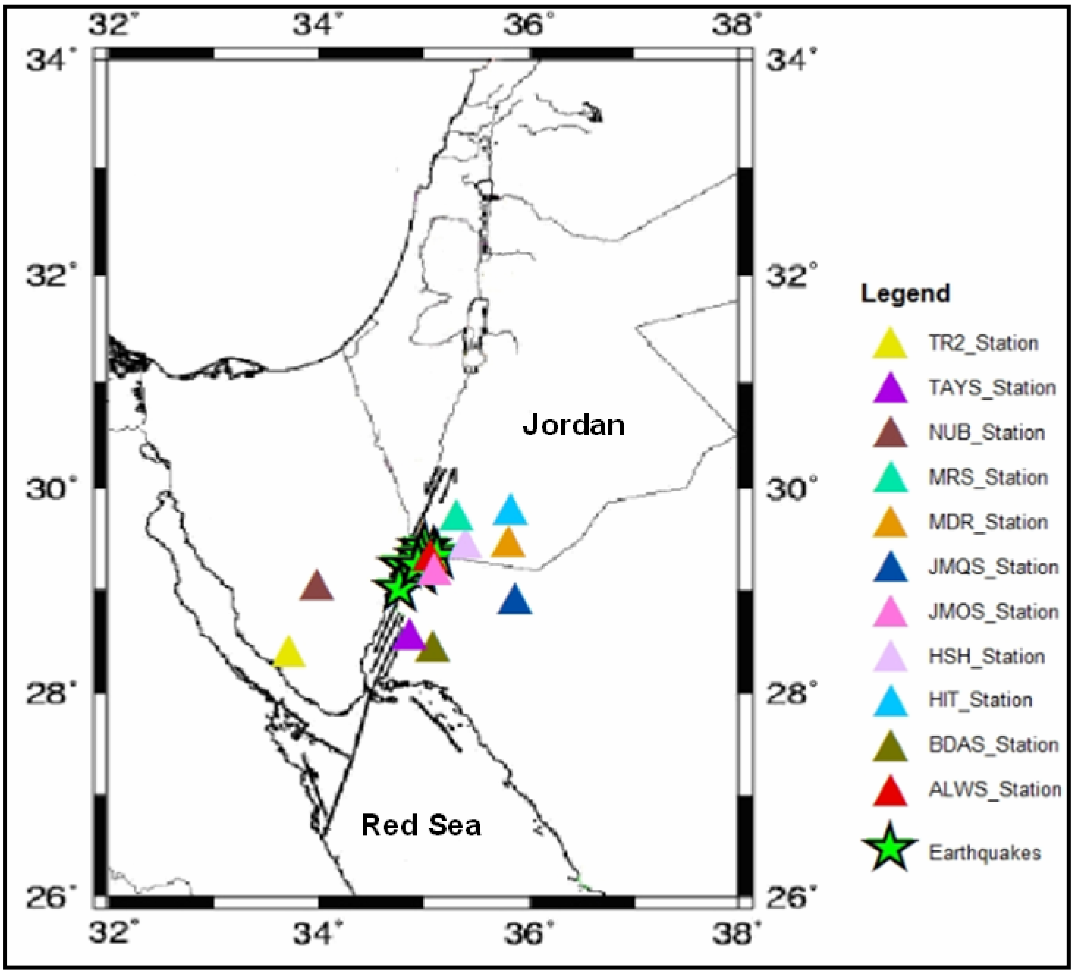


Figure 4.30: Location of seismic stations tested for the efficiency with respect to the earthquakes used.

4.6 Relocation results and discussion

There are many problems about instrumental seismicity including the accuracy and homogeneity of earthquakes data, but relocation process of earthquakes whenever possible is useful if based upon information about a better adequate crustal model and the collection of more extensive data about the events.

Earthquakes in the Gulf of Aqaba were relocated after reexamining the P and S arrival times, testing the efficiency of stations used to determine the location of Aqaba events, calculating the average value of Vp/ Vs, and choosing the best crustal model for the study area.

The 17 events from the Gulf of Aqaba were relocated using data from Egypt, Saudi Arabia, and Jordan stations (figure 4.31). The data set was analyzed using Seisan software (the coordinates along with statistical indicators about the relocation quality are summarized in table 4.7). Determinations for each event from all sources are summarized in table 4.8.

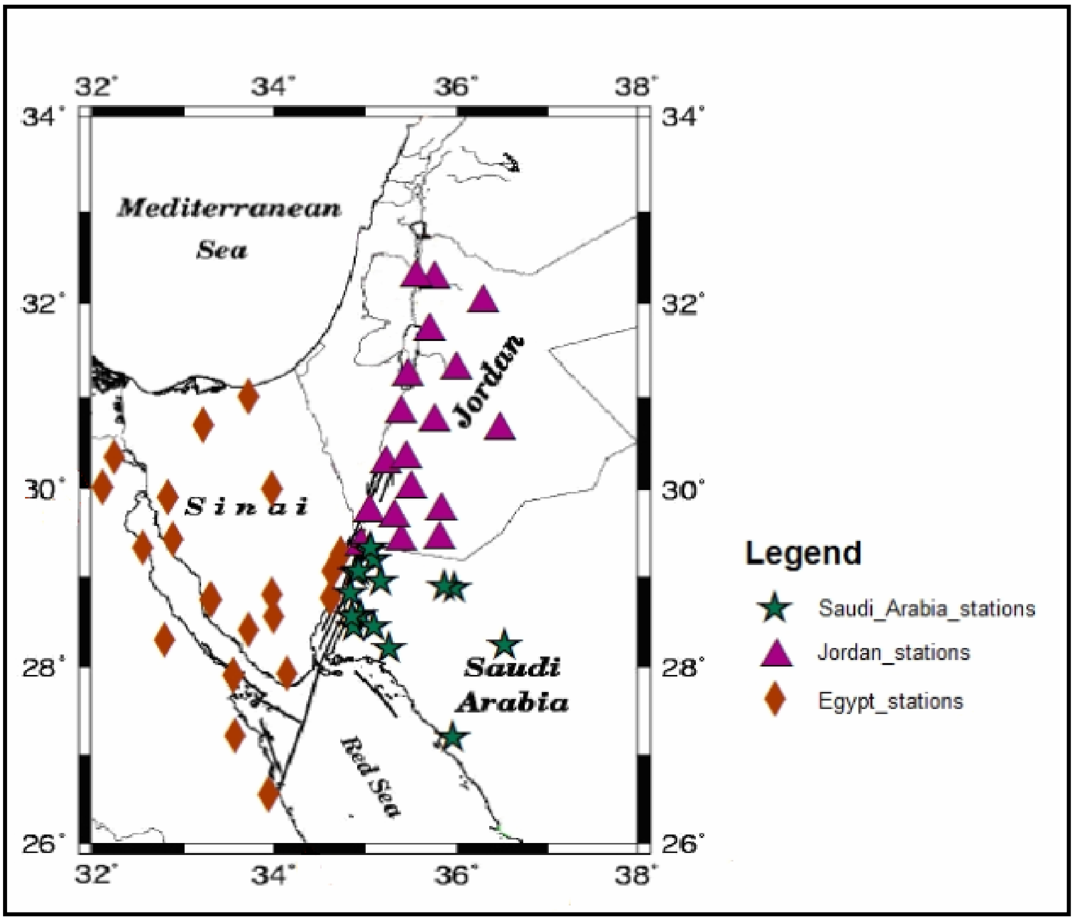


Figure 4.31: Main national seismological stations networks in the area which were used in relocation process showing in principle excellent azimuthal coverage with respect to the Gulf of Aqaba epicenters.

Table 4.7: The Coordinates of the newly determined hypocenters using El-Isa et al (1986) model, and the associated RMS values of the relocation map on Figure 4.32.

Date	Time	Lat	Long	RMS
09/01/2004	09:54:36	29.175	34.972	0.23
10/01/2004	22:28:31	28.497	34.673	0.28
16/01/2004	15:18:43	28.574	34.686	0.15
21/01/2004	02:42:56	29.874	34.762	0.28
24/01/2004	15:51:09	29.411	34.981	0.21
26/01/2004	12:25:56	29.347	35.113	0.30
29/01/2004	18:47:07	28.484	34.972	0.16
09/02/2004	00:42:41	28.895	34.805	0.37
10/02/2004	21:10:23	29.254	34.907	0.17
10/02/2004	21:27:17	29.266	34.946	0.18
10/02/2004	22:55:45	29.303	34.780	0.15
11/02/2004	03:54:40	29.985	35.391	0.27
11/02/2004	10:45:40	28.951	34.756	0.17
12/02/2004	01:04:54	29.218	34.875	0.00
15/02/2004	19:52:39	29.320	34.986	0.17
25/02/2004	04:38:10	29.388	35.178	0.36
25/02/2004	14:53:46	29.018	34.761	0.13

Table 4.8: The Coordinates of the previously determined hypocenters of the selected earthquakes.

Date	JSO-Jordan		NRIAG-Egypt		SNSN-Saudi Arabia	
	Lat	**Long**	**Lat**	**Long**	**Lat**	**Long**
09/01/2004	29.15200	34.95000	29.09000	34.94000	29.09430	34.85670
10/01/2004	28.52800	34.89800	28.47000	34.60000	28.52100	34.77140
16/01/2004	28.57000	34.94800	28.56000	34.63000	28.50970	34.66880
21/01/2004	29.79000	34.67100	29.77000	34.59000	29.77170	34.55430
24/01/2004	29.26100	34.88000	29.22000	34.89000	29.24030	34.81380
26/01/2004	29.26700	34.85200	29.24000	34.92000	34.84560	18.31590
29/01/2004	28.49500	34.84300	28.65000	34.60000	28.56200	34.66760
09/02/2004	28.97600	34.79800	28.88000	34.66000	28.85320	34.74100
10/02/2004	29.18000	34.86900	29.14000	34.74000	29.11820	34.78230
10/02/2004	29.16900	34.88000	29.14000	34.77000	29.11450	34.79140
10/02/2004	29.17600	34.85000	29.15000	34.72000	29.11640	34.79380
11/02/2004	30.06000	34.68700	30.20000	34.62000	30.18110	34.49840
11/02/2004	28.90300	34.85700	28.77000	34.68000	28.74990	34.75170
12/02/2004	29.23300	34.90500	29.14000	34.78000	29.11630	34.80630
15/02/2004	29.25200	34.86100	29.17000	34.91000	29.20830	34.80250
25/02/2004	29.23200	34.88600	29.17000	34.78000	29.17370	34.82000
25/02/2004	28.97900	34.76300	28.90000	34.72000	28.90800	34.71870

From figure 4.32, it can be noticed that most of the events are located on the eastern side of the Gulf and are trending in N-S direction along the Gulf of Aqaba. These results are in agreement with previous results concerning the relocation of the first Gulf of Aqaba swarm of 1983. (Abou Karaki ,1987, 1995; Abou Karaki, et al., 1993).

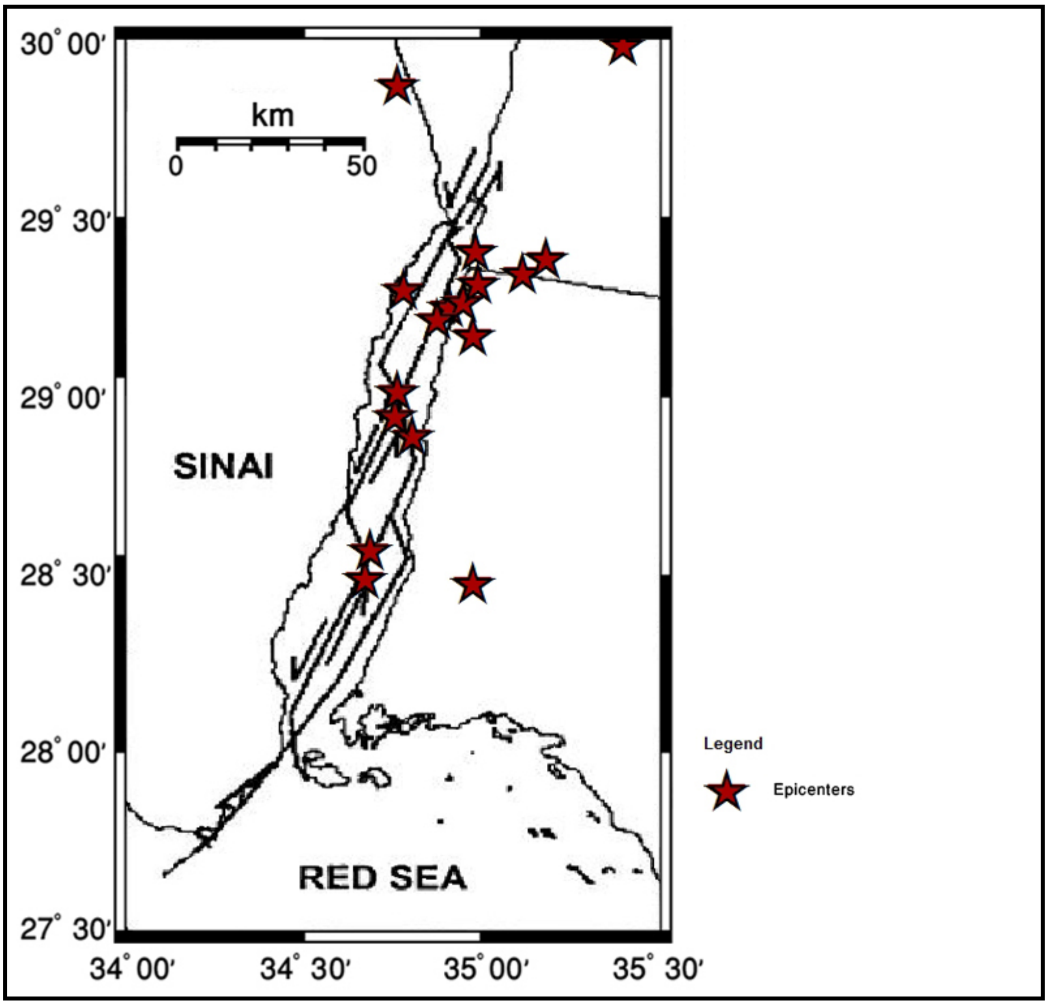


Figure 4.32: Epicentral distribution of the events listed in table 4.7 after relocation process (this Work).

Comparisons were made between the result of the relocation and previous determination of these events by JSO, SNSN, NRIAG (figures 4.33and 4.35).

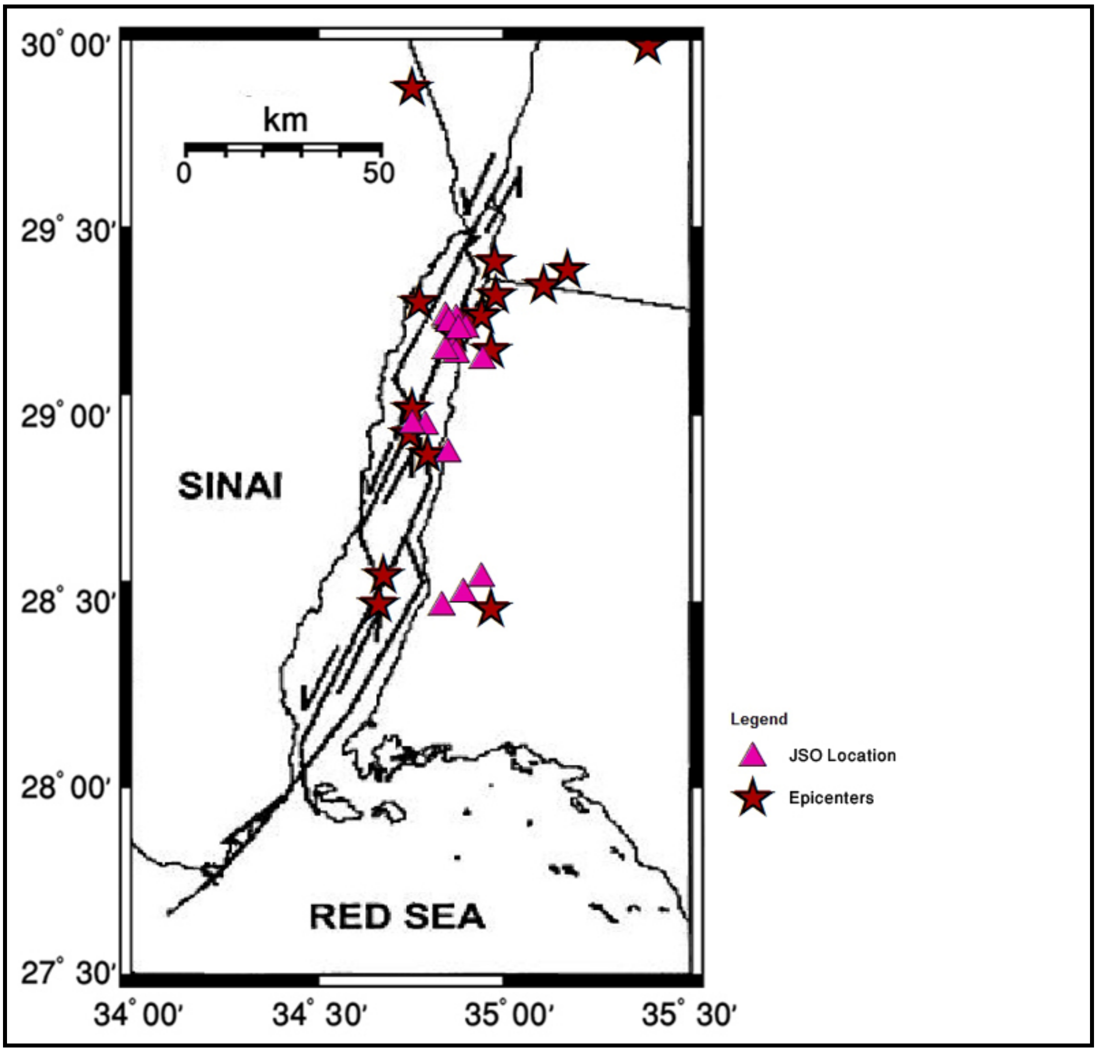


Figure 4.33: Comparison of location of Aqaba events between this work (star signs) and JSO results.

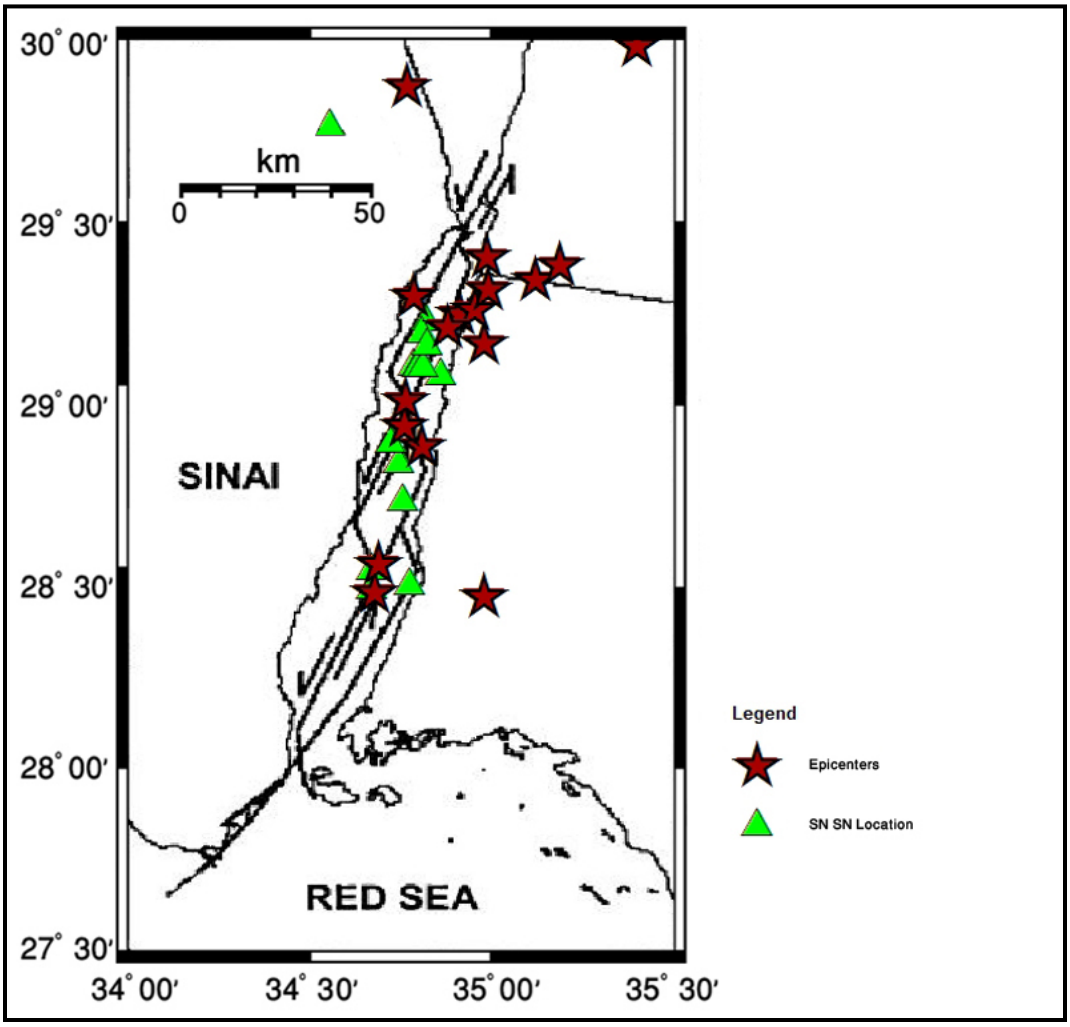


Figure 4.34: Comparison of location of Gulf of Aqaba events between this work (star signs) and Saudi results.

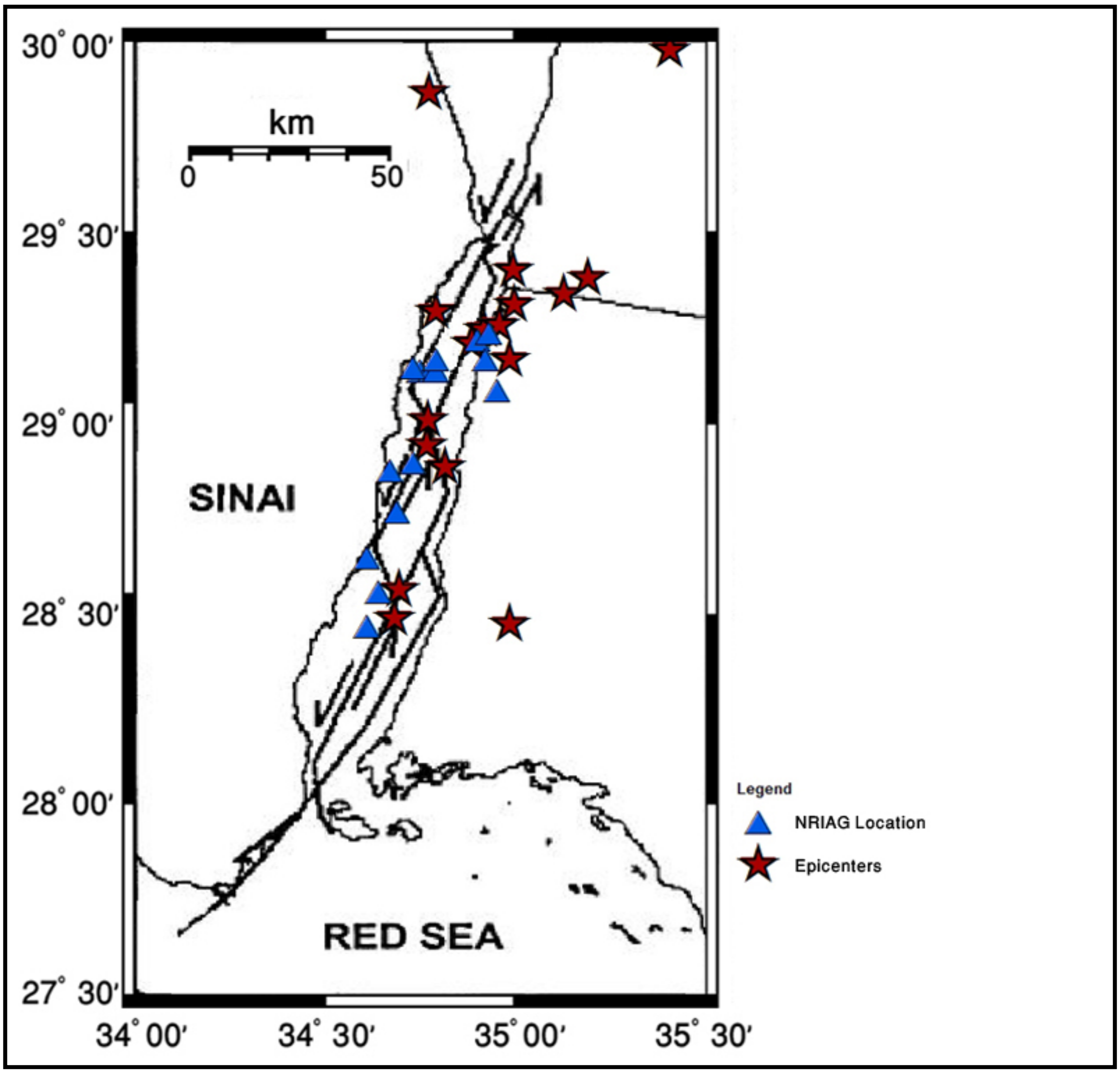


Figure 4.35: Comparison of location of Aqaba events between this work (star signs) and Egypt results.

Figures from (4.36 to 4. 44) show the correlation between different sources for the events which were located by each of the above mentioned national seismic monitoring organizations and this work (star sign). It is noticed that most of the resulting seismicity locations can be correlated with tectonic and structural elements in the area. The maximum discrepancy between the new locations and previously determined ones is about 37 km.

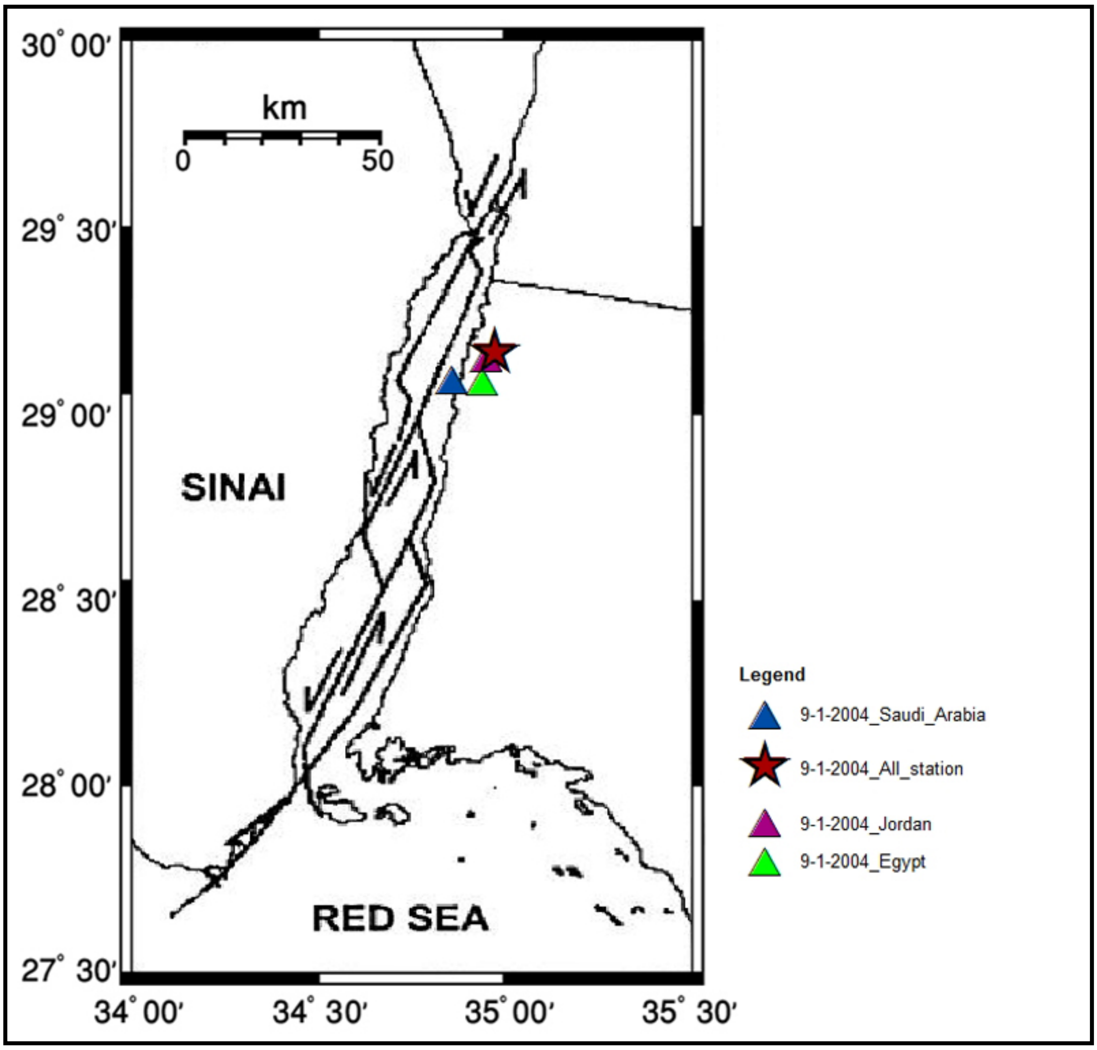


Figure 4.36: Comparison between previous determination of the location of 9-1-2004 event and this work (star sign).

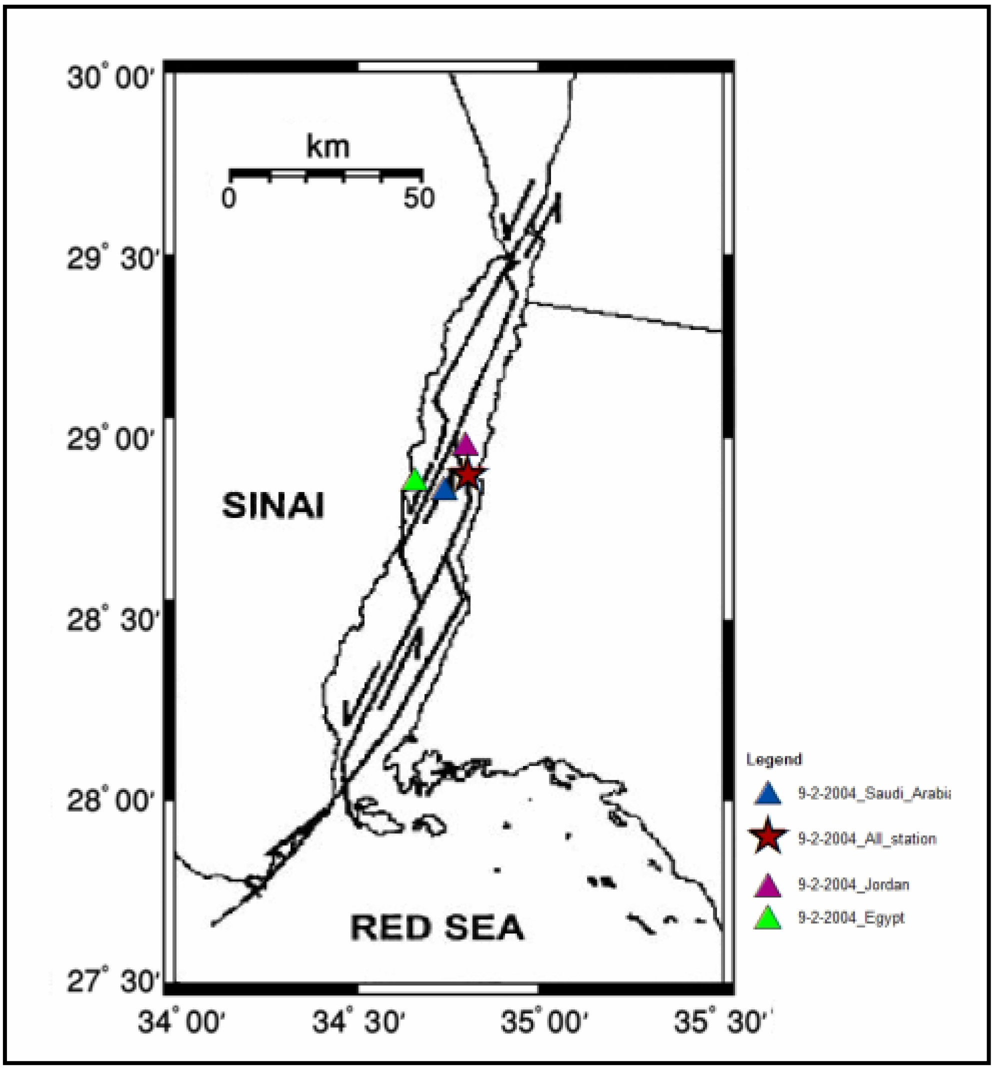


Figure 4.37: Comparison between previous determination of the location of 9-2-2004 event and this work (star sign).

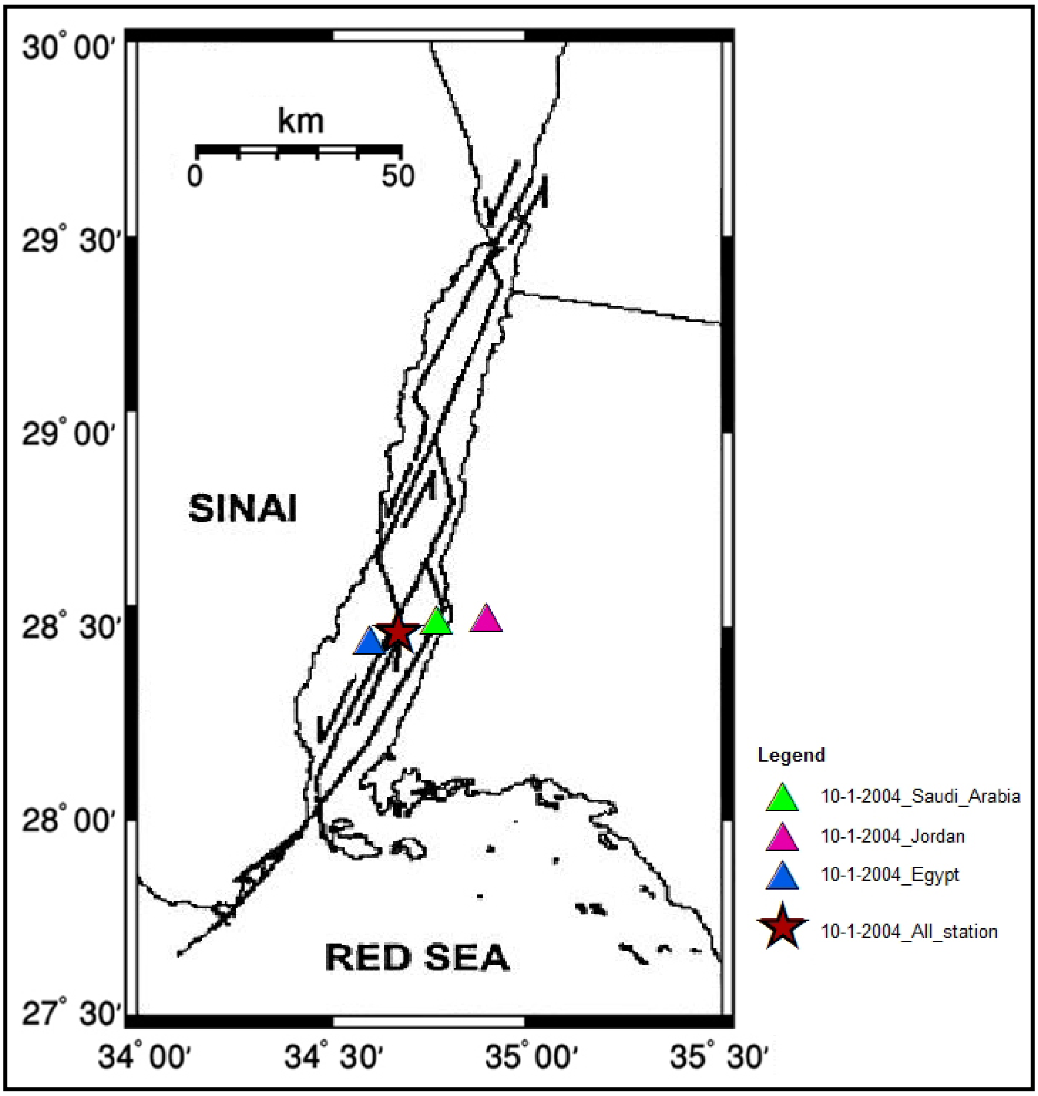


Figure 4.38: Comparison between previous determination of location of 10-1-2004 event and this work (star sign).

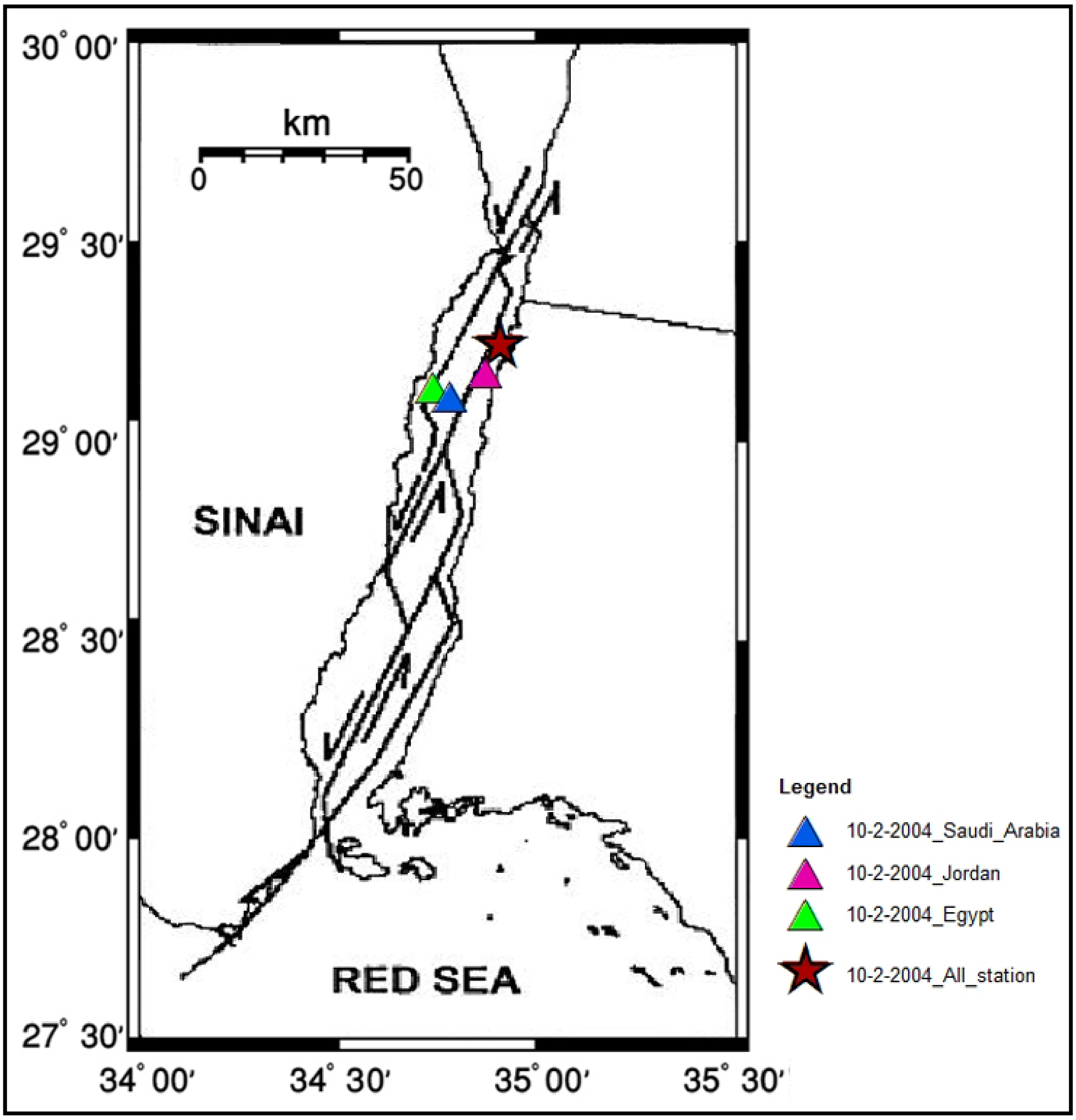


Figure 4.39: Comparison between previous determination of location of 10-2-2004 event and this work (star sign).

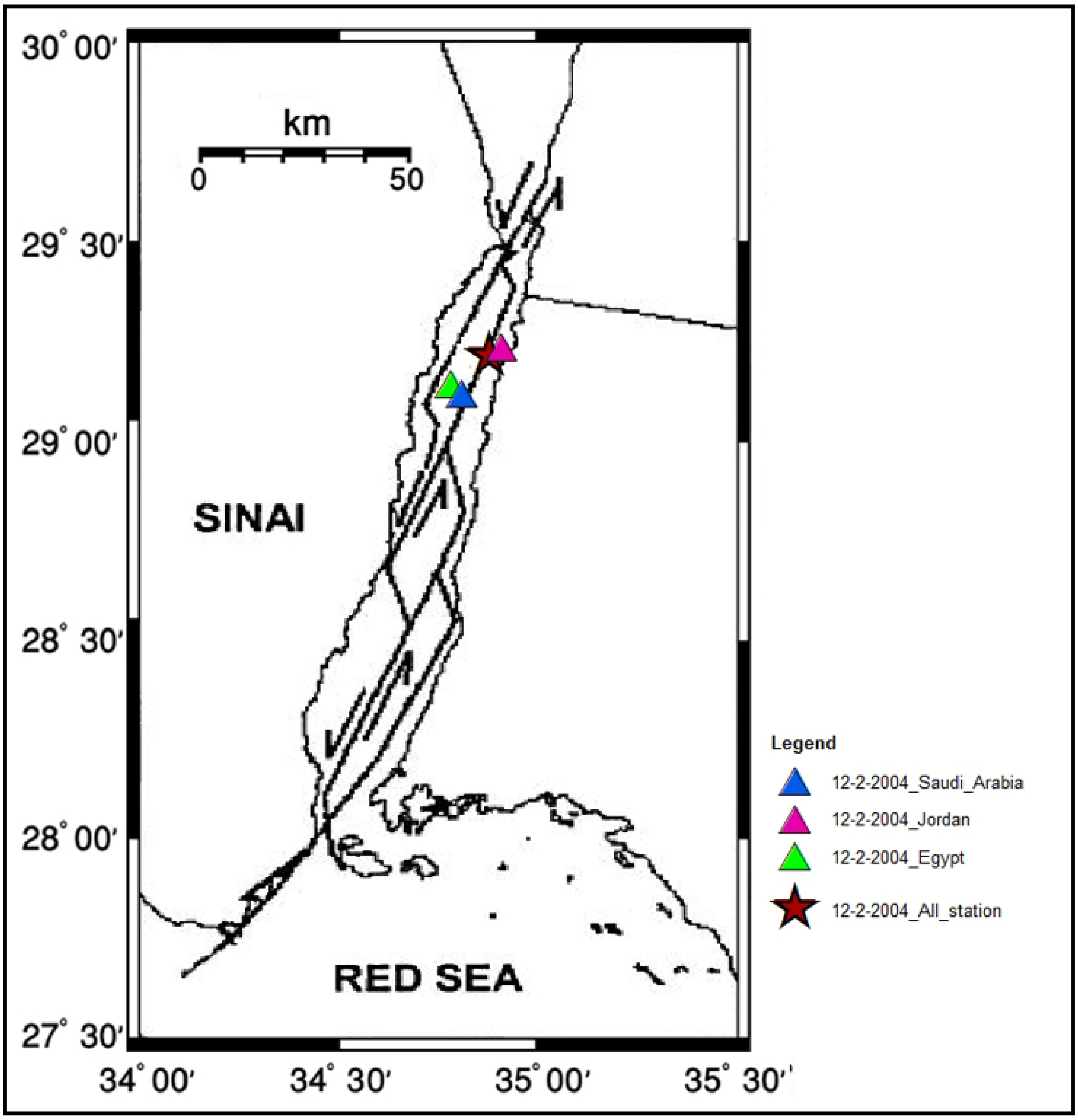


Figure 4.40: Comparison between previous determination of location of 12-2-2004 event and this work (star sign).

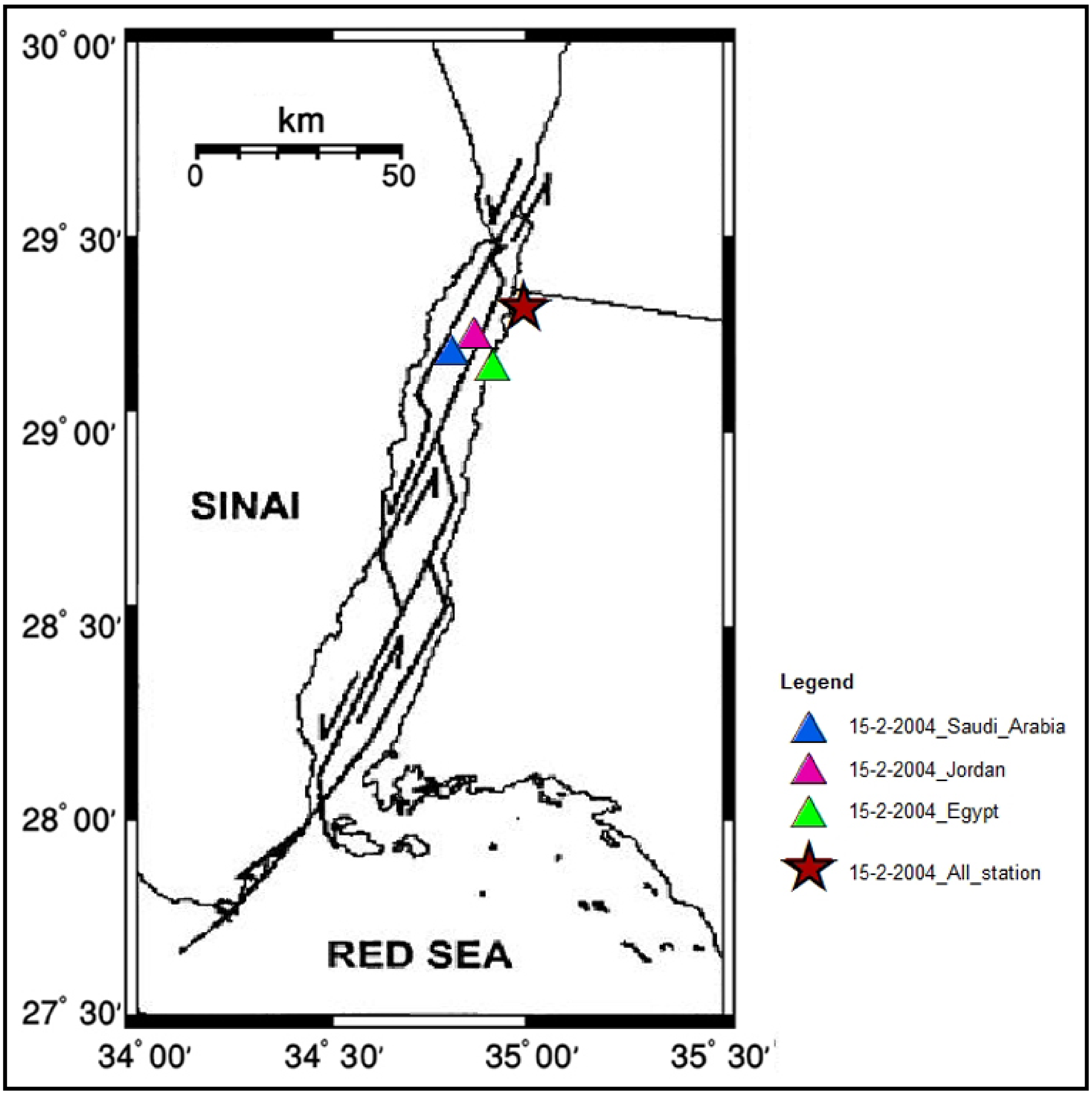


Figure 4.41: Comparison between previous determination of location of 15-2-2004 event and this work (star sign).

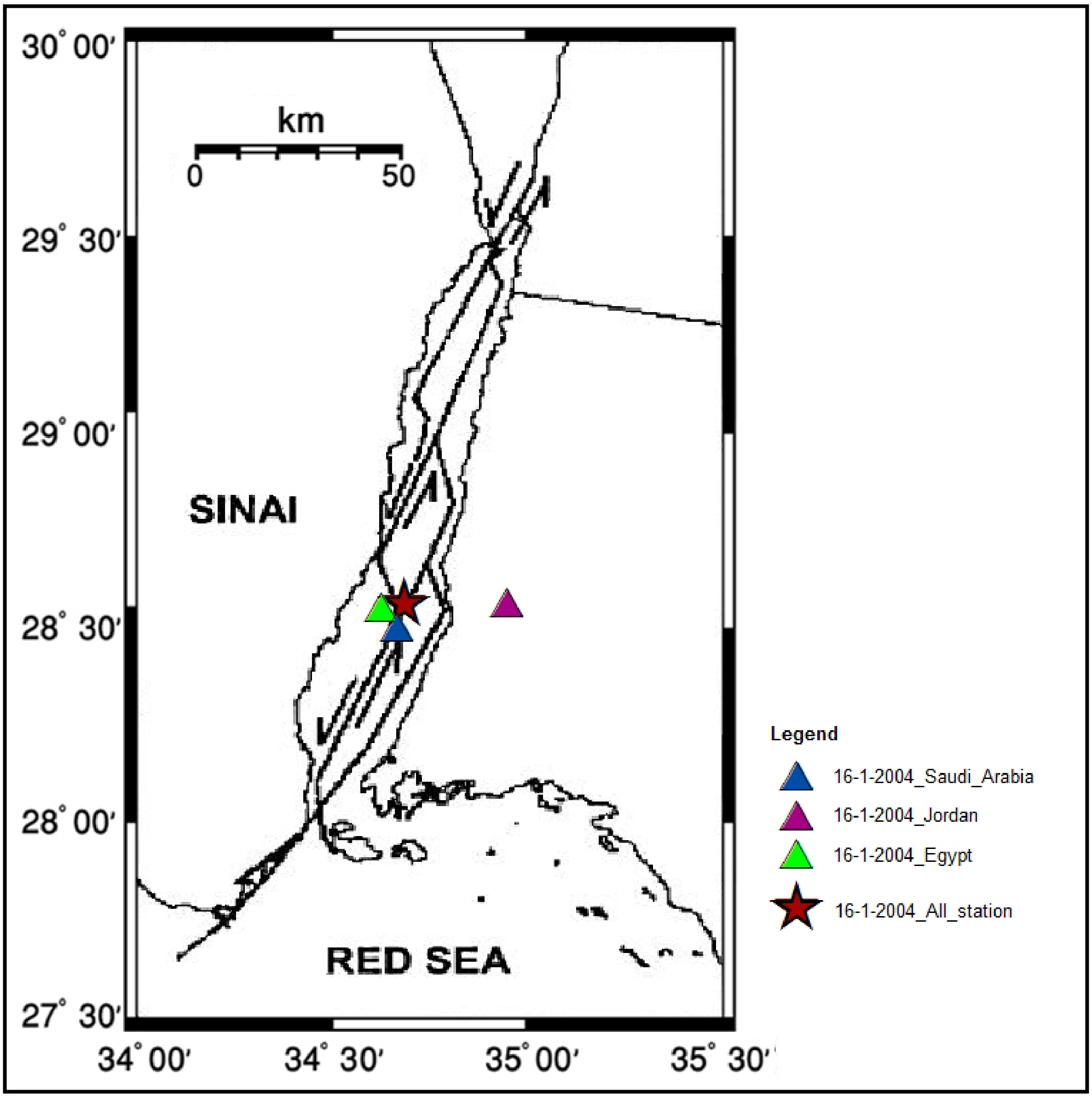


Figure 4.42: Comparison between previous determination of the location of 16-1-2004 event and this work (star sign).

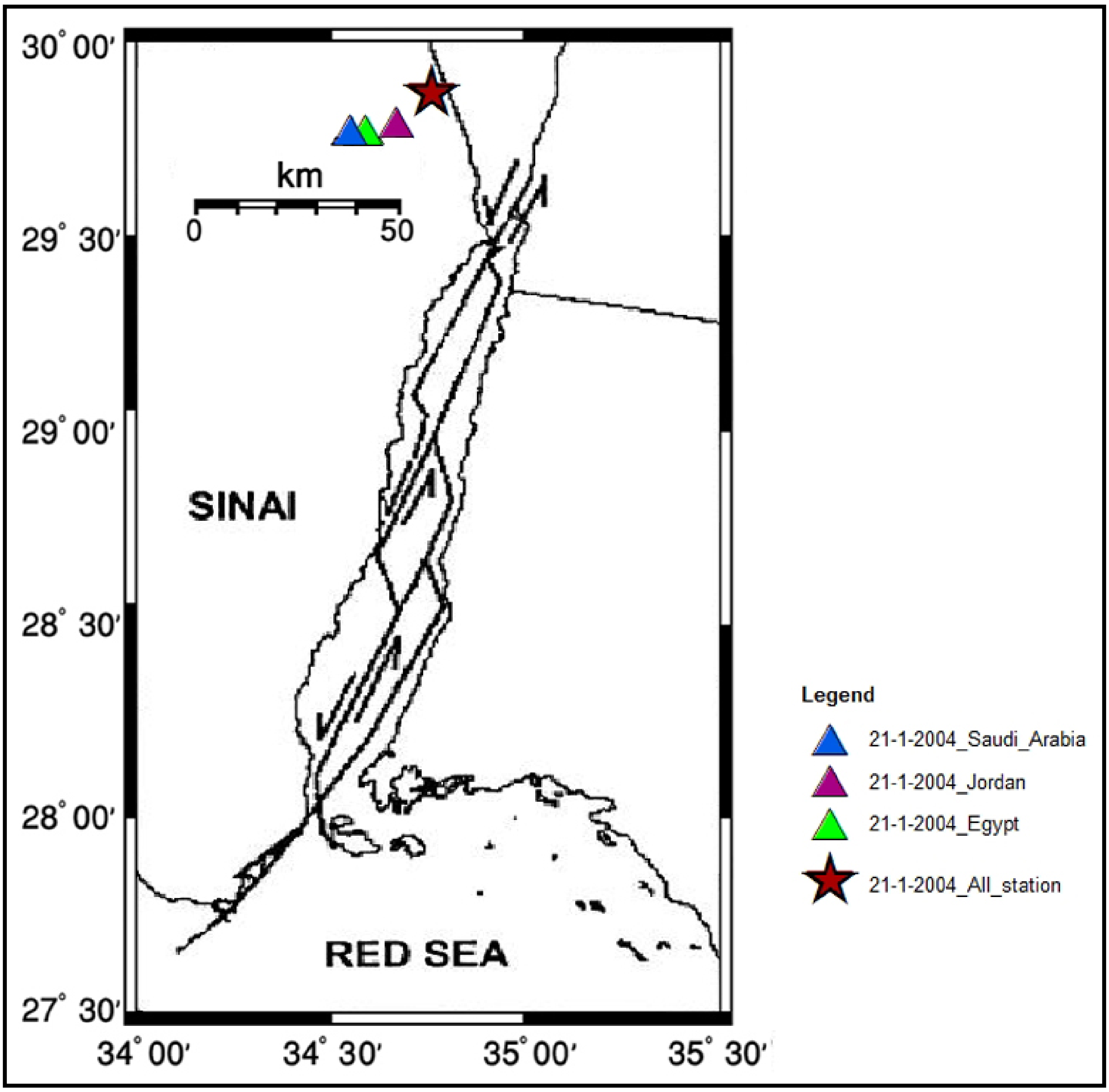


Figure 4.43: Comparison between previous determination of the location of 21-1-2004 event and this work (star sign).

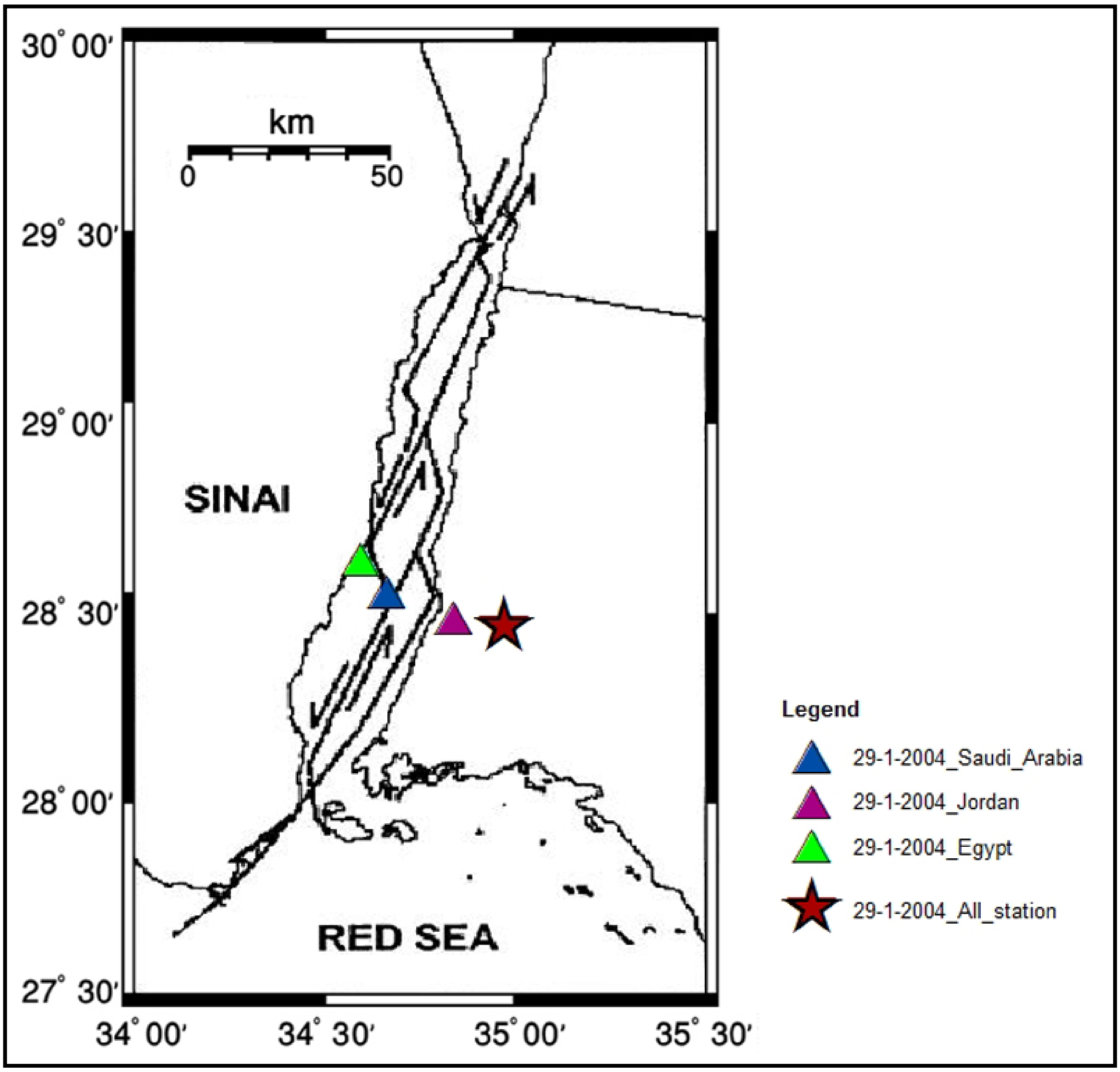


Figure 4.44: Comparison between previous determination of location of 29-1-2004 event and this work (star sign).

An overview was made to some earthquakes to show the ellipse of errors from different sources of data (figure 4.45 – 4.47).

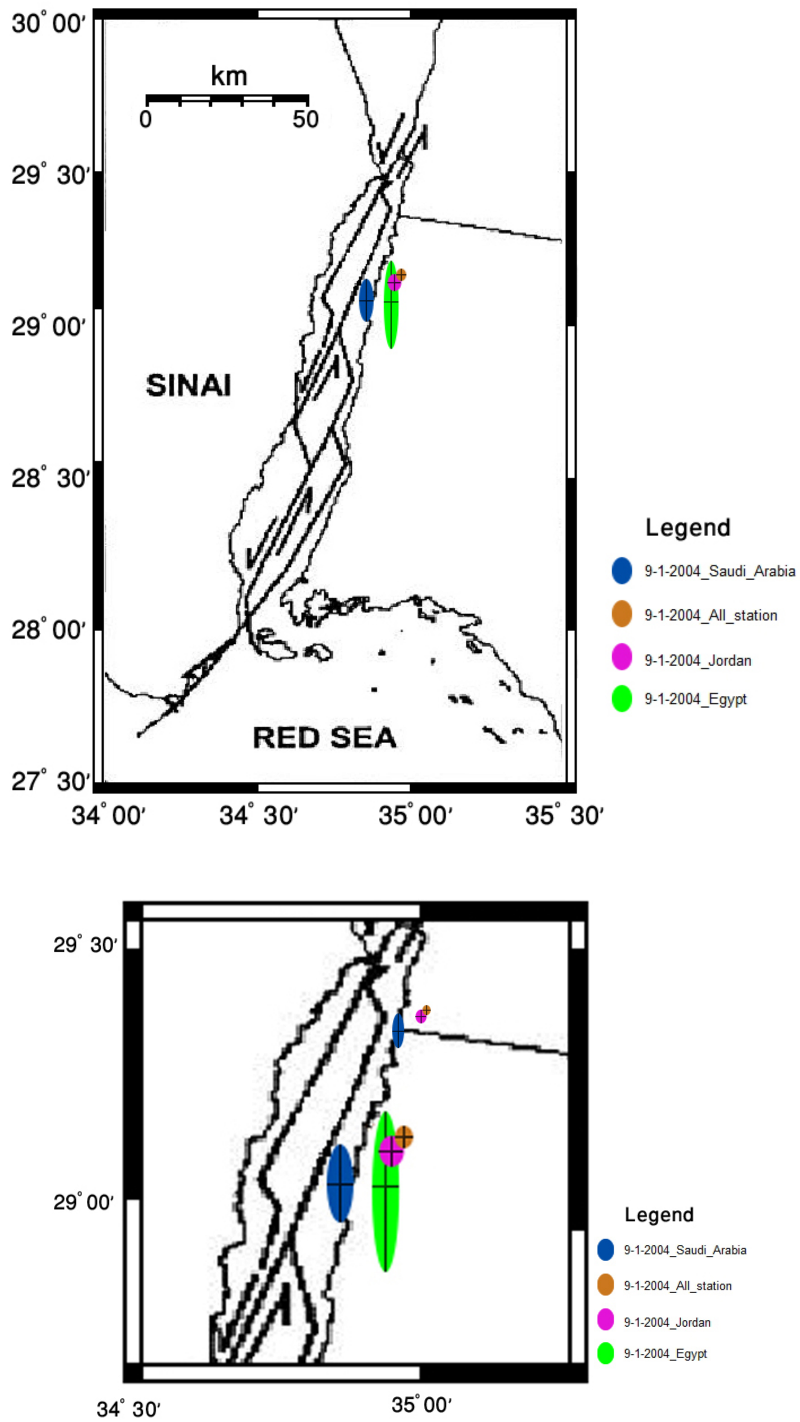


Figure 4.45: Ellipses of error of 9-1-2004 earthquake using different sources of data.

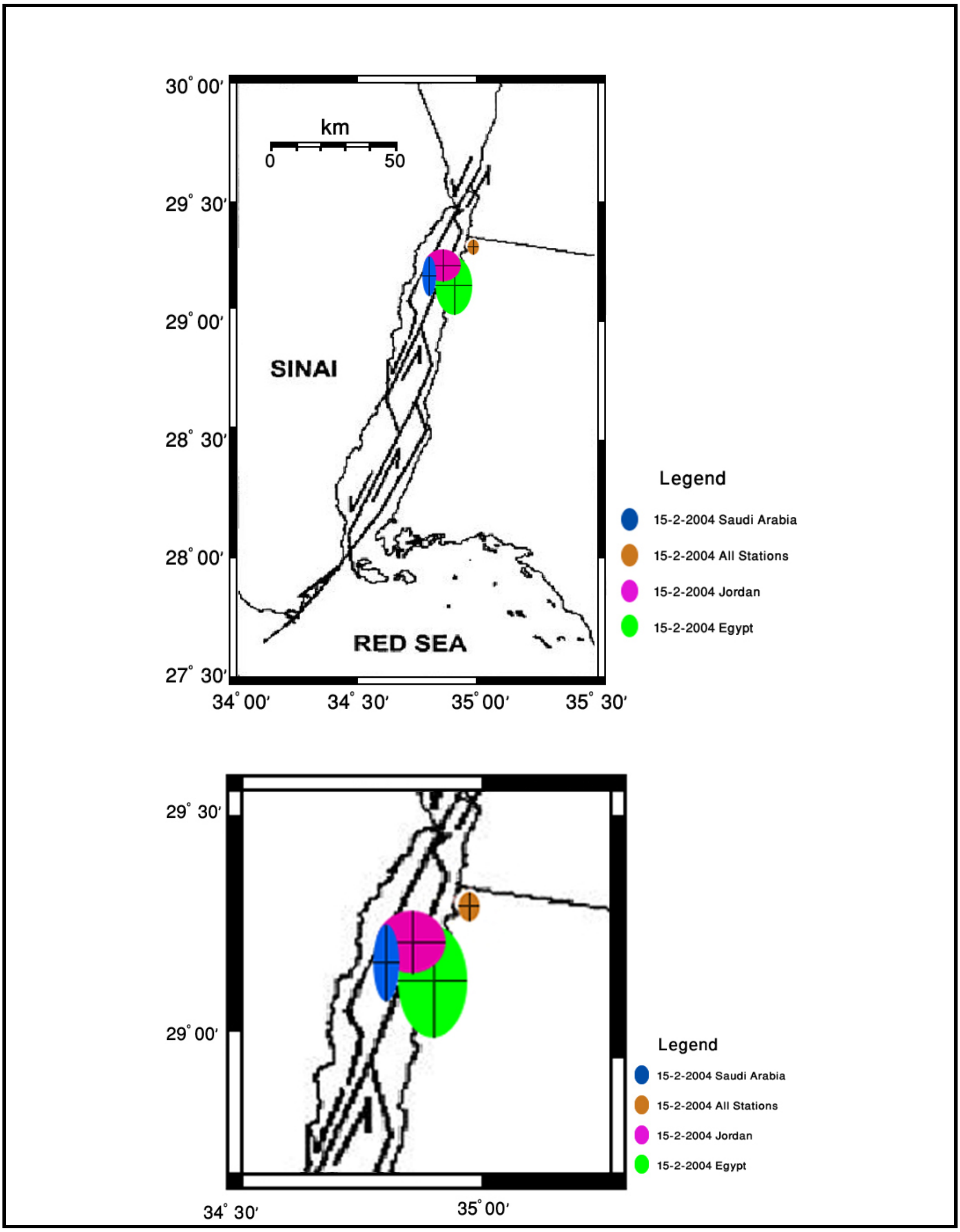


Figure 4.46: Ellipses of error of 15-2-2004 earthquake using different sources of data.

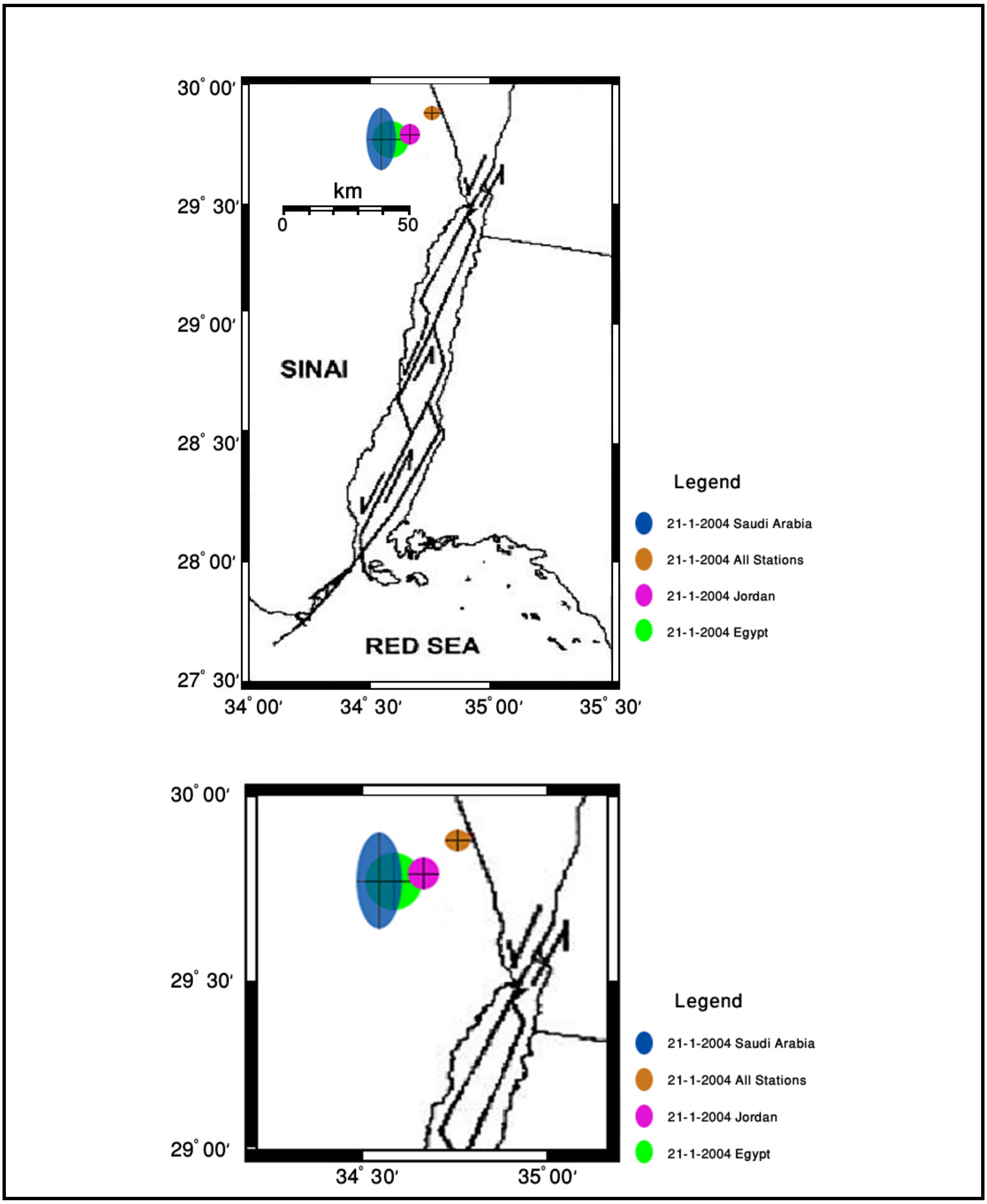


Figure 4.47: The Ellipses of error of 21-1-2004 earthquake using different sources of data.

4.7 Analysis of most recent events in Gulf of Aqaba (15/7/2010 event)

A new event occurred in Gulf of Aqaba in 15-7-2010 with a magnitude of 4.2 Ml and a depth of 10 Km. It was analyzed and relocated after comparison was made between data from European-Mediterranean Seismological Centre (EMSC) and the Jordan Seismological Observatory (JSO). Relocation process was made using data from JSO stations and from European-Mediterranean Seismological Centre. The stations were taken into consideration within 200 km distance. Figure 4.48 shows the result in comparison with the previous determination from EMSC and JSO locations.

From figure 4.48 we can notice that there are discrepancies in the location of the event from different sources. This work locates and after taking into consideration all stations from different sources puts the earthquake on the western side of the Gulf, but the EMSC's location puts it on the eastern side. JSO data was not used in the previous EMSC location.

Table 4.9 represents the root mean square error of time residuals from different sources.

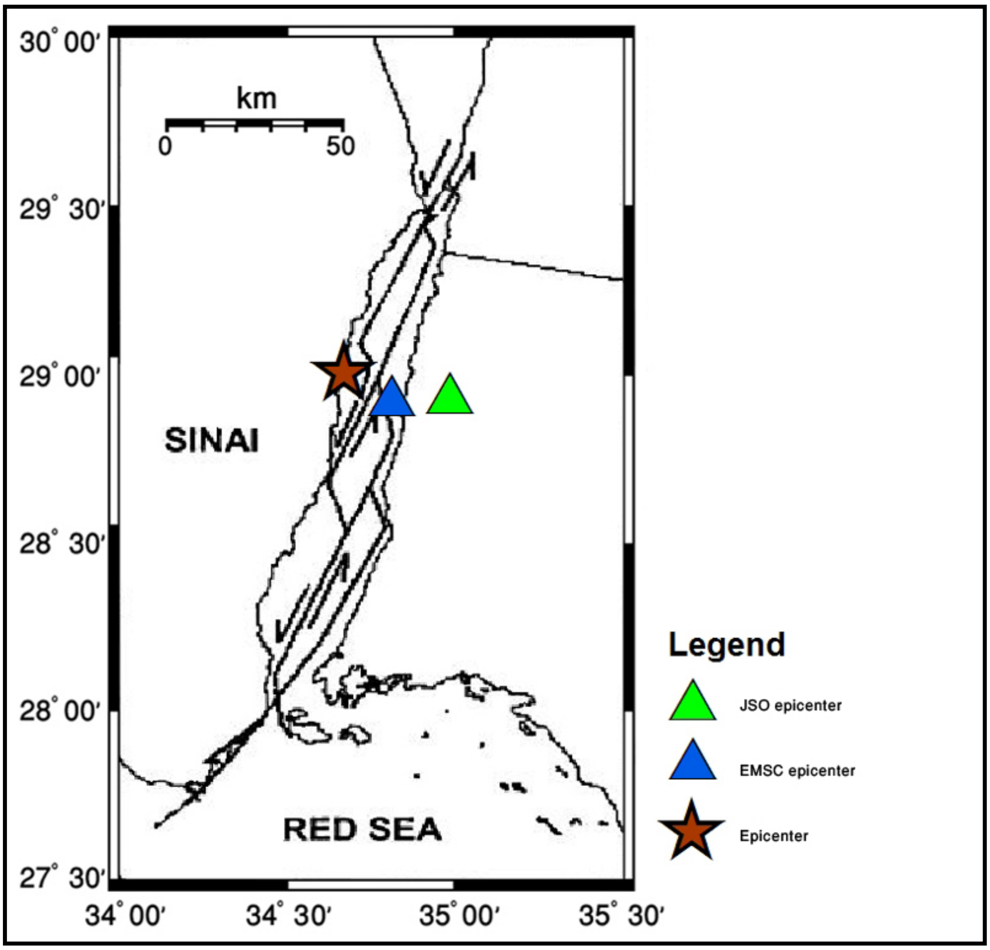


Figure 4.48: Comparison between previous determination of location of 15-7-2010 event and this work (star sign).

Table 4.9: Root mean square error of time residuals from different sources of 15-7-2010 event.

Source	Latitude	Longitude	RMS
Previous (EMSC)	28.94	34.81	0.52
Previous (JSO station)	28.949	35	0.18
This work	29.016	34.66	0.31

CHAPTER 5

SEISMIC HAZARD ASSESSMENT OF GULF OF AQABA AREA

CHAPTER 5

SEISMIC HAZARD ASSESSMENT OF GULF OF AQABA AREA

5.1 Introduction

Seismic hazard analysis is the computation of occurrence per unit time of certain levels of ground shaking caused by earthquakes. Earthquake hazard analysis involves the determination of ground motion parameters such as Peak Ground Acceleration (PGA) and spectral acceleration for a given area or specific site location, which are important parameters for the design of civil engineering structures. It can be estimated by using different approaches. The first one is the deterministic approach; it does not take into account the uncertainties in the size, location, occurrences, and times of seismic events and other characteristics of future earthquakes (Shah and Dong, 1984). Instead, it adopts the most conservative values for these factors that entail extremely large design requirements. The second one is the probabilistic approach. According to this method, the earthquake may be specified in terms of either its source characteristics or its effect at a particular site.

The probabilistic approach is used for the assessment of seismic hazard in Aqaba region. The methodology used in most probabilistic seismic hazard analysis was first defined by Cornell, 1968 and Reiter, 1990 and it consists of four steps:

1- Definition of source zones, in which, the area under investigation is divided into seismic source zones according to its seismicity and tectonics.
2- Recurrence characteristics of source zones, based on earthquake catalogue, the seismicity within each source zone is studied to determine the magnitude-frequency relationships and seismic rate.

3- Estimation of earthquake effect at site, to relate the expected ground motion at site during an earthquake to the magnitude of earthquake and its distance from site, a local attenuation relationship is chosen. In addition, the uncertainty of the ground motion values is an important parameter for the analysis.

4- Determination of the seismic hazard based on the fact that the probability of an earthquake of a given magnitude to occur on a source zone within any given distance is proportional to the fraction of the area of the zone that occurs within the range of the site, the hazard analysis can be determined. From the result it is possible to determine the probability of any intensity or acceleration value being exceeded, assuming seismic process to follow a Poisson's distribution.

The result that may be obtained by probabilistic method is the probability distribution of a maximum ground motion intensity parameter for a certain site and the generation of iso-acceleration or iso-seismal contours.

5.2 Definition of seismic zone and seismic hazard parameters

5.2.1 Seismotectonic source zone

A seismic zone is defined as a seismically homogenous area, in which every point within the source zone is assumed to have the same probability of being the epicenter of a future earthquake. An ideal delineation of seismic source zones requires a complete understanding of the geology, tectonics, paleoseismology, historical and instrumental seismicity, and other neotectonic features of the region under study (Frankel, 1995). However, it is not always possible to compile detailed information in all these fields for the majority of areas of the world. Thus, frequently, seismic source zones are determined with two fundamental tools; a seismicity profile and the tectonic regime of the region under consideration.

Based on the distribution of earthquakes in Jordan and its vicinity and the tectonics in the region, seismic zones can be determined. Determination of these zones depends on tectonic features, location of earthquakes, and the solution of focal mechanisms (Erdik, 1984). From figure 5.1, the distribution of earthquakes can be correlated with the main tectonic elements of the Jordan Dead Sea Transform area and surrounding (Gulf of Suez, the Gulf of Aqaba, Wadi Araba, the Dead Sea and the Jordan Valley, and Southwest Syria).

The main seismotectonic zones in this study (figure 5.1) can be summarized as follows:

1- Gulf of Suez: This Gulf suffered from intensive structural deformation and the earthquakes are concentrated beneath this part of the Gulf. The focal mechanisms of the 1969 and 1972 earthquakes which occurred in the southern part of the Gulf of Suez indicate normal faulting parallel to the Gulf axis (Jackson and McKenzie, 1984).

2- Gulf of Aqaba: The Gulf of Aqaba has been the most active seismic zone in the area over the last three decades; the Gulf is characterized by a swarm type activity. The variety of the focal mechanism solutions reflects the complexity of the structure within the Gulf. Some mechanisms show normal faulting and thus are attributed to the faults that form the boundaries of the major basins in the Gulf; others indicate left lateral motion of the transform fault (Salamon, et al., 2003) (figure 5.2).Yet left lateral motion with a reverse component is also present (Abou Karaki, 1987, 1995; Abou Karaki, et al. 1993).

3- Wadi Araba Fault: Wadi Araba Fault extends over 160 km from the Gulf of Aqaba to the Dead Sea and provides morphological evidence of essentially strike-slip motion (Klinger, et al., 2000). It is characterized by its low seismicity compared with the surrounding area, despite clear indications of recent faulting (Gerson, et al., 1993).

4- Dead Sea Basin: It is characterized by its double fault system; the Wadi Araba Fault from the east and the Jordan Fault from the west. Swarm and a main-shock/after-shock type of earthquake activity characterize the Dead Sea seismogenic zone (Al-Hefnawy, et al., 2006).

5- Jordan Valley zone: It links the Hula basin in the north and the Dead Sea Basin in the south. Earthquake activity along the Jordan valley proper is low compared with the Dead Sea to the south (Al-Hefnawy, et al., 2006). This seems to be true at least for the last few decades.

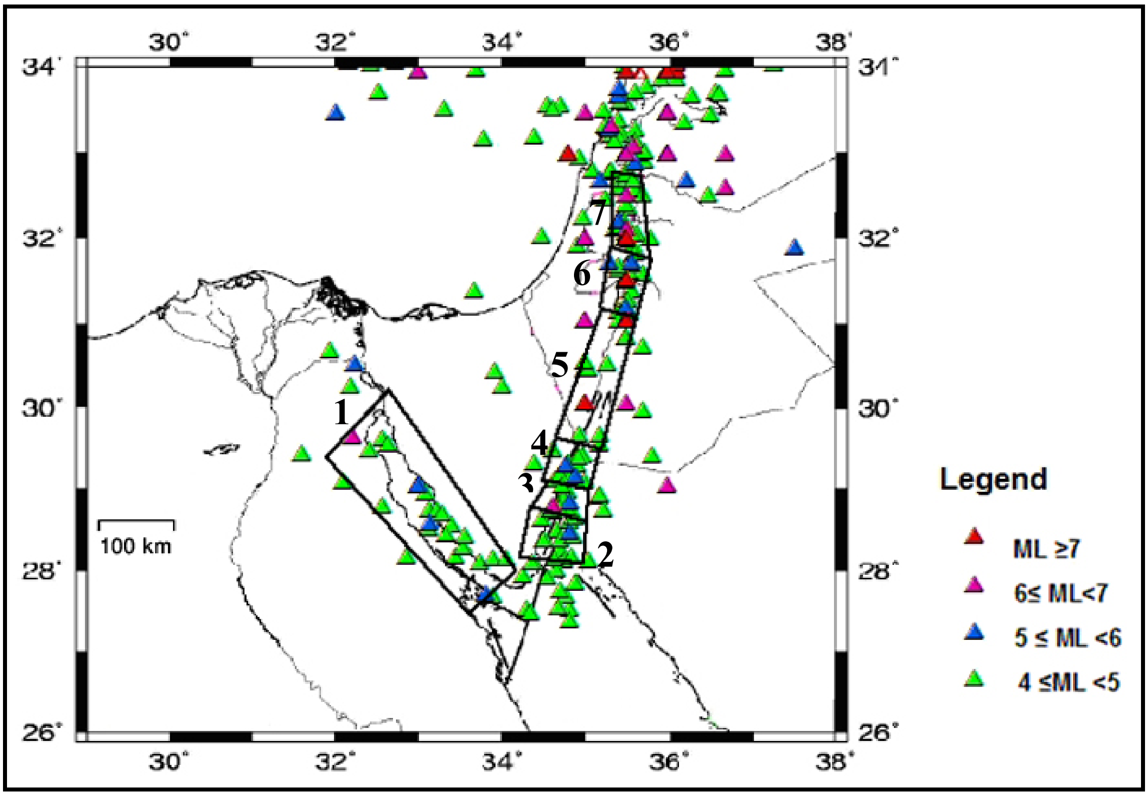


Figure 5.1: Distribution of earthquakes and seismic sources used for seismic hazard assessment (data from JSO stations).

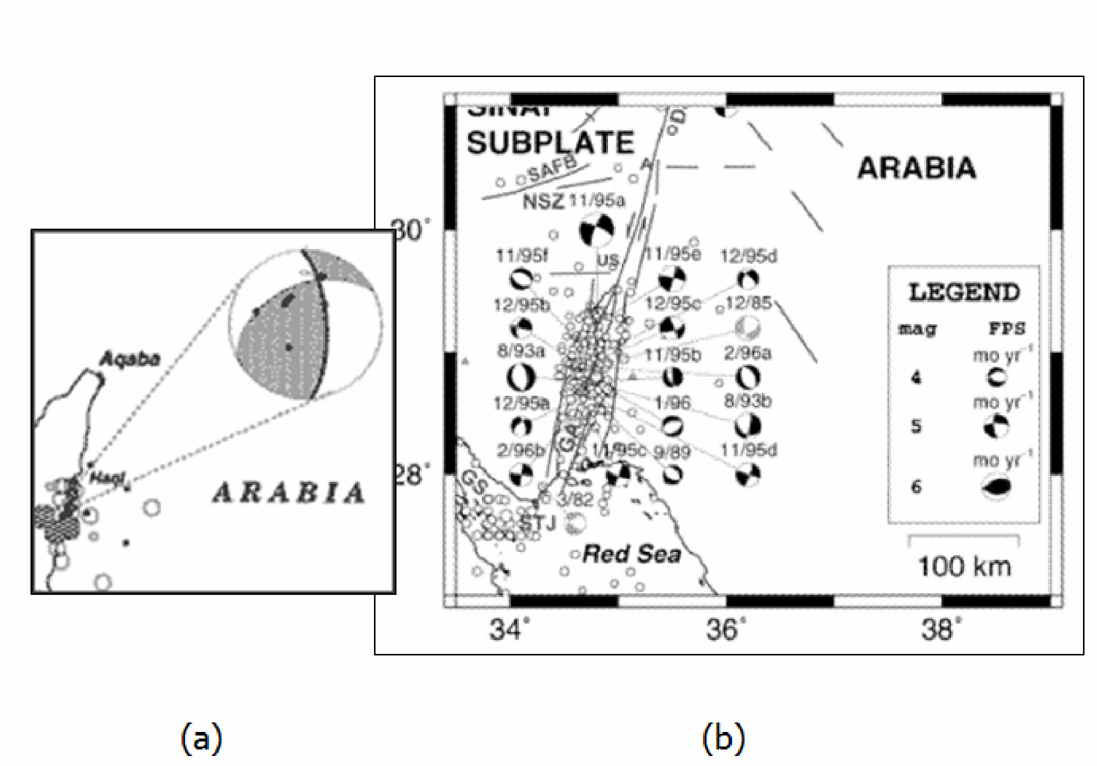


Figure 5.2: The different focal mechanisms for the Aqaba Gulf, (a) represent the focal mechanism for 1983 earthquake (figure based on Abou Karaki (1987) and Abou Karaki (1995) source: http://www.pellamuseum.org/Pella_Museum/Earthquakes/Page3.htm), and (b) for 1985, 1993, 1995 modified from (Salamon et al. 2003).

5.2.2 Seismic hazard parameters

The main idea of the probabilistic hazard analysis is to estimate the probability that certain peak ground acceleration will be exceeded during a known period of time at a certain site.

For each determined zone, seismic hazard parameters (for historical and instrumental earthquakes) were estimated in order to assess the hazard in this study. These parameters are used to study main shock earthquakes after removing foreshock and aftershock earthquakes to achieve the independency and Poisson's distribution of the data (Gulkan and Erdik, 1986).

A brief description is presented for all parameters as follows:

1- The frequency-magnitude relationship (b – parameter)

The frequency–magnitude relationship is the term to quantify the seismicity of a seismogenic zone. For each seismic source, the magnitude distribution was supposed to be exponential. A linear regression analysis was carried out to estimate the coefficients of the Gutenberg–Richter relationship between magnitudes and their cumulative frequency of occurrence. This equation is expressed by Gutenberg and Richter (1965) as follows:

$$\log_{10} N(m) = a - b\,m \qquad (5.1)$$

where N (m) is the number of earthquakes having magnitude (m) over a certain time interval, a and b are empirical parameters (Gutenberg and Richter, 1965). In this study, Wizmap program was used to obtain the b-value. Wizmap program, is a program for investigating earthquake catalogues and macroseismic data sets. It Draws polygonal zones and obtains analyses of the seismicity within each zone, with respect to maximum magnitude, Gutenberg-Richter curve, depth distribution. The b-parameter is important for quantification of seismicity (Allen, et al., 1965) and for prediction of the time of occurrence of the main shock when the b-parameter decreases before the main shock (Suyehiro, 1966; Papazachos, 1975).

The a-parameter was determined and it depends on the level of seismicity, the length of time taken into account and the extent of an area. But it is not important for seismic hazard assessment calculations in this study (Miyamura, 1962).

The value of b- parameter estimated by using the Gutenberg – Richter formula (equation 5.1) are summarized in table 5.1.

2- Activity rate of earthquakes

The rate of activity is the frequency of occurrence of earthquakes as a function of magnitude. The earthquake occurrence is assumed to be a Poisson stationary process. This assumption implies that the earthquakes are considered to be random events, each independent of the other, with constant mean rate, in order to use this hypothesis, the aftershocks have to be excluded from the analysis. The assumption of is commonly used in the zones where the actual stage of the seismic process is unknown. The mean occurrence rate is then estimated simply by dividing the total number of events in the catalogue for each zone with magnitude ≥ m, (N (m)), by the time span,(T), covered by the catalogue:

$$\lambda (m) = \frac{N (m)}{T} \qquad \textbf{(5.2)}$$

The annual activity rate of earthquakes of all zones is listed in Table (5.1) after removing the foreshocks and aftershocks.

3-The Upper Bound Magnitude

The Upper Bound Magnitude (m1) is the Maximum magnitude expected to occur at each seismic zone. It can be calculated using two methods; the first one is assuming that the maximum observed magnitude in every zone is the maximum expected event in the future (and this magnitude which enters to the seismic hazard program). The second one is using the fault rupture–magnitude relationship. This relationship has been developed to relate maximum earthquake magnitude on a fault to rupture length of the fault. This last method is followed using Ambraseys and Barazangi (1989) equation that was derived for the Middle East region:

$$Ms = 4.63 + 1.43 \log_{10} L \qquad \textbf{(5.3)}$$

where L is the rupture length in (km) and Ms is the surface wave magnitude. The type of magnitudes used for the determination of seismic hazard in this study and associated with attenuation equations used is the surface wave magnitude and moment magnitude. The type of magnitude which was used to establish the earthquake catalogue is the local magnitude, as a result, the following equations (Raid, et al., 1988) and (Scordilis, 2006) was used to convert the local magnitude to surface wave magnitude and moment magnitude:

$$\mathbf{Ms = 1.069ML - 0.524} \qquad \mathbf{(5.4)}$$

$$\mathbf{Mw = 0.67\ Ms + 2.07} \quad \mathbf{(3 \le Ms \le 6.1)} \qquad \mathbf{(5.5)}$$

$$\mathbf{Mw = 0.99\ Ms + .08} \quad \mathbf{(6 \le Ms \le 8.2)} \qquad \mathbf{(5.6)}$$

Table 5.1: seismic sources and their related parameters for Earthquakes of M≥ 4 for historical and instrumental data up to 2010.

Zone No	Name of the Zone	Beta value	Annual rate of activity	Max Magnitude	Probability of Activity
1	Suez Zone	2.14	0.57	6.8	1
2	Aqaba 1	2.20	1.10	6.0	1
3	Aqaba 2	2.00	0.80	7.2	1
4	Aqaba 3	2.30	0.70	6.0	1
5	Wadi Araba	0.57	0.01	6.9	1
6	Dead Sea	0.85	0.01	6.9	1
7	Jordan Valley	0.71	0.02	7.2	1

4- Peak ground acceleration

Lee et al. (2003) stated that the ground motion is induced by seismic energy release at the source. It is usually measured by magnitude, seismic shaking intensity, and peak ground acceleration, which can be quantified using seismograms or

accelerograms. The most often used measure of the strength of ground motion is peak ground acceleration. Peak ground accelerations are generally calculated using empirical attenuation equations that describe the behavior of the ground motions as a function of the magnitude of the earthquake, and the distance between the site and the seismic source (the causative fault). Peak ground acceleration is one of the steps in the seismic hazard analysis used to describe the attenuation of the ground motion intensity. Attenuation of ground motion depends on many factors such as the fault mechanism, path of the seismic waves and site geological conditions (Lee, et al., 2003). The most common means of estimating the ground motion in engineering practice, including probabilistic seismic hazard analysis, is the use of an attenuation relation or ground motion model which is a mathematical expression that relates a specific strong motion parameter of ground shaking to seismological parameters of an earthquake (Lee, et al., 2003). An attenuation relation can be described by an expression of the form

$$\mathbf{Y= c_1 e^{c2M} R^{-c3} e^{-c4r} e^{c5F} e^{c6S} e^{\varepsilon}} \qquad \mathbf{(5.4)}$$

where Y is the strong motion parameter of interest, M is earthquake magnitude, r is a measure of source to site distance, F is a parameter characterizing the type of faulting, S is a parameter characterizing the type of local site condition, **ε** is a random error term, R is a distance term and c1, c2, c3, c4, c5, c6 can be defined as functions of M and R (Lee, et al., 2003).

Attenuation relationships tend to be regionally specific according to the geological and tectonic structures and faulting styles in the region under study and site specific that they may be established for particular soil condition.

The attenuation equations used in this study are Ambraseys, et al., (1996) equation and Boore, et al., (1997) equation. These equations are representative for Dead

Sea Transform region as (Leonov, 2000) results, and used by many researchers, such as Jaradat, et al., 2008 (see figure 5.3). The application of Ambraseys, at al., (1996) and Boore, et al., (1997) equation requires magnitude values to be given in term of surface-wave magnitude (Ms) and moment magnitude (Mw). To handle the required magnitude a conversion must be made, as most of magnitude values in the Jordanian seismic catalogue are given in terms of local magnitude (ML).

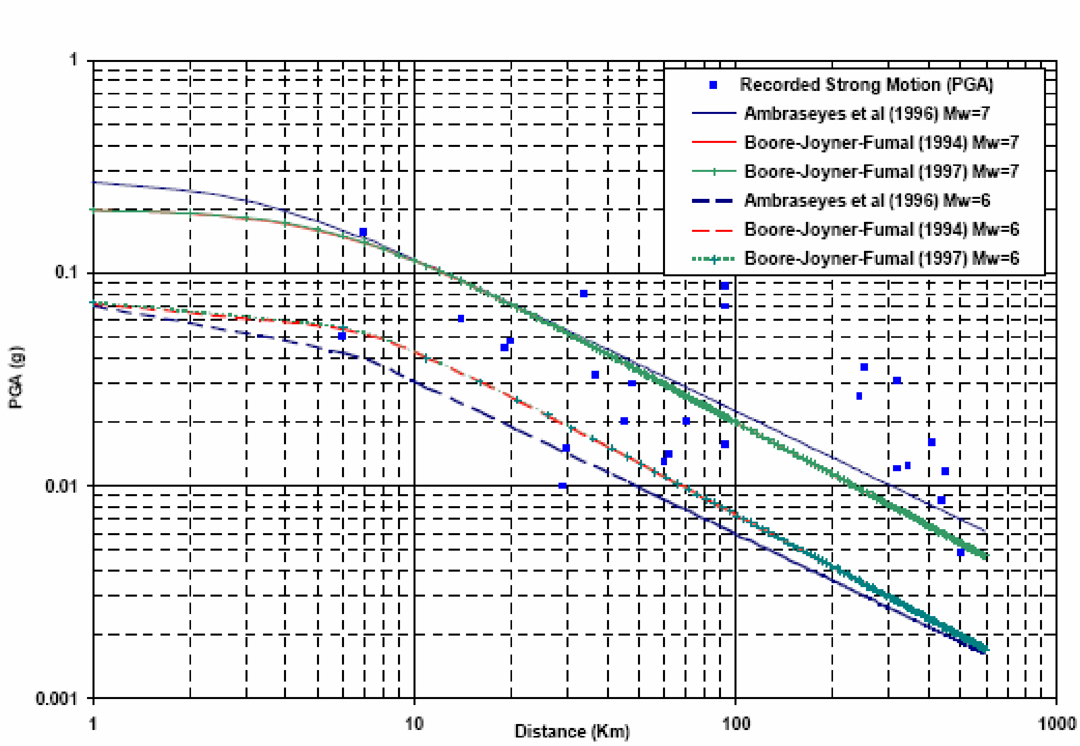


Figure 5.3: Comparison between the attenuation equations of Ambraseyes, et al., (1996), Boore-Joyner-Fumal (1994 and 1997) against GPA values of strong motion stations from Jordan and Israel, using Mw=6 and 7 (Jaradat, et al., 2008).

5.3 Seismic hazard maps

5.3.1 Methodology (EZ-FRISK Program)

For probabilistic seismic hazard assessment EZ-FRISK (A Software for Earthquake Ground Motion Estimation) was used (EZ-FRISK User's manual, 2008).

The EZ-FRISK program contains three main capabilities:

· Seismic Hazard Analysis

· Spectral Matching

· Site Response Analysis

About the seismic hazard analysis, the program calculates the earthquake hazard at a site under certain assumptions specified by the user. These assumptions involve identifying where earthquakes will occur, what their characteristics will be, and what the associated ground motions will be. EZ-FRISK performs both probabilistic and deterministic seismic hazard calculations.

The construction of a probabilistic ground-motion hazard map for a region follows a sequence of analyses beginning with the selection of an earthquake catalog and ending with the mapping of calculated probabilistic ground-motion values (Hanson, et al., 1992). An integral part of this process is the creation of sources used for the calculation of earthquake recurrence rates and ground motions. These sources consist of areas and lines that are representative of geologic or tectonic features and faults. The earthquake sources are modeled as either points located randomly within seismically homogeneous source zones or as finite length ruptures that occur randomly along linear fault segments.

After the design of the sources, it is necessary to arrange the coordinate points in a particular order compatible with the input format for the EZ-FRISK program to be entered.

The input data for EZ-FRISK program includes minimum and maximum magnitude, minimum and maximum depth, annual rate of activity, beta, probability of activity and rupture and length for fault for every zone, the last input determined from equation 5.4.

The calculated values for earthquake hazard are displayed as iso-acceleration contours expected to be exceeded during typical economic life time of structures. This program is based on the assumption that the site acceleration has a Poisson distribution with a mean annual rate. The program can accommodate any attenuation relationships and generate a table of peak ground accelerations and the cumulative distribution of the acceleration for each specified site.

5.3.2 Seismic hazard assessment results and discussion

5.3.2.1 Seismic hazard assessment results

For probabilistic seismic hazard assessment EZ-FRISK was used to calculate peak ground acceleration of point source model (The zones taken into consideration are of area form). The calculated values for earthquake hazard are displayed as iso-acceleration contours expected to be exceeded during typical economic life time of structures. This program is based on the assumption that the site acceleration has a Poisson distribution with a mean annual rate.

Probabilistic ground motion analysis were made for the Gulf of Aqaba with 0.1^{o} X 0.1^{o} grid and drawing seismic hazard maps. These maps were prepared according to Ambraseys, et al., (1996) and Boore, et al., (1997) attenuation equations and from the seismic hazard parameters determined for each zone. Figure (5.4) and (5.5) show the iso-acceleration lines with the economic life of structures equal to 10% probability of exceedance in 50 year using the attenuation equations for Ambraseys, at al., (1996) and Boore, et al., (1997).

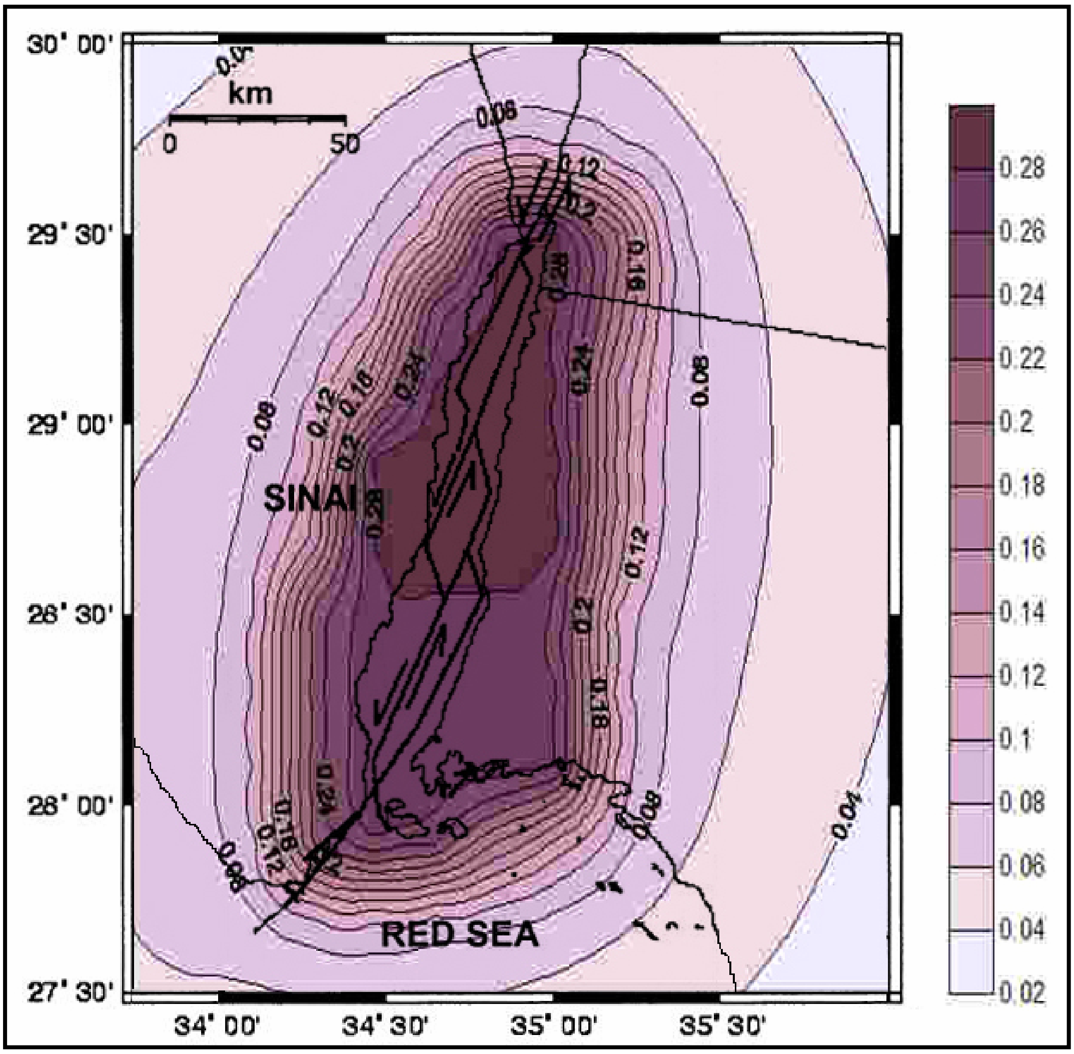


Figure 5.4: Peak ground acceleration distribution in the Gulf of Aqaba in g unit, with 10% probability of exceedence using Ambraseys, et al., 1996 attenuation equation.

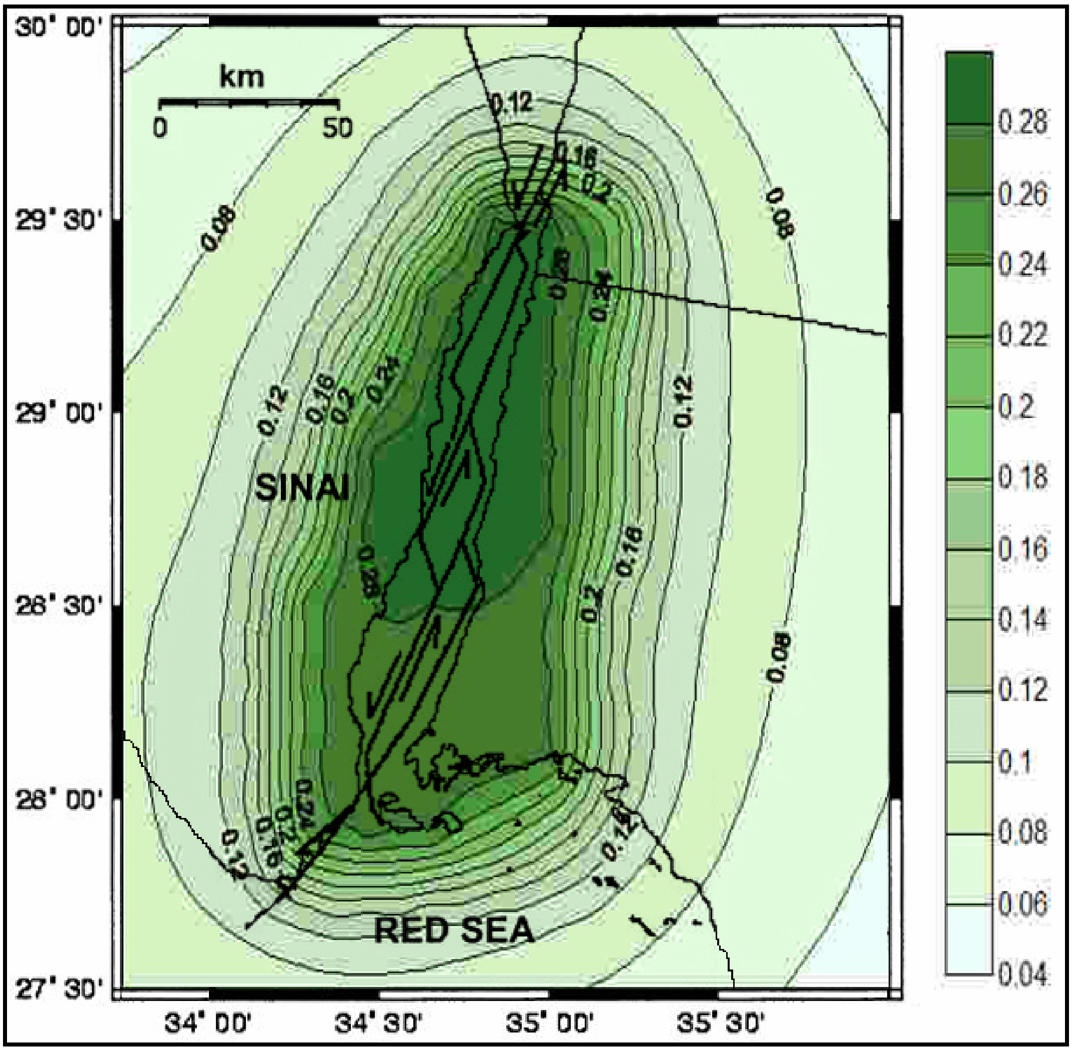


Figure 5.5: Peak ground acceleration distribution in the Gulf of Aqaba in g unit, with 10% probability of exceedence using Boore, et al., 1997 attenuation equation.

The resulting seismic hazard maps show that the value of PGA is high in the Gulf of Aqaba and the highest value of PGA is in the northern and central part of the Gulf of Aqaba with maximum peak ground acceleration value around 0.293 g using Ambraseys equation and about 0.286 g using Boore equation for 10% probability of exceedence (50 year period).

These values of PGA are due to seismic activity and tectonics in the central and northern parts of the Gulf which is characterized by the junction with Wadi Araba segment of the DST Fault. The hazard is concentrated in the Gulf and decreases away from it.

5.3.2.2 Comparison between previous works and this study

For the Middle East region, many probability maps have been produced and seismic hazard analysis have been done, such as for Turkey by Gulkan and Erdik (1986), for Iraq by Mohmoud et al. (1987), for Palestine by Shapira (1981), Ben – Menaham et al. (1982), Shapira (1983 a, 1983 b), Shapira (1984), Shapira and Lomnitz (1984), Arieh and Rabinowitz (1989), and Rabinowitz and Steinberg (1991). Figure 5.6 shows the PGA values for the Middle East region, the hazard in Jordan is moderate in comparison with the region surrounding it.

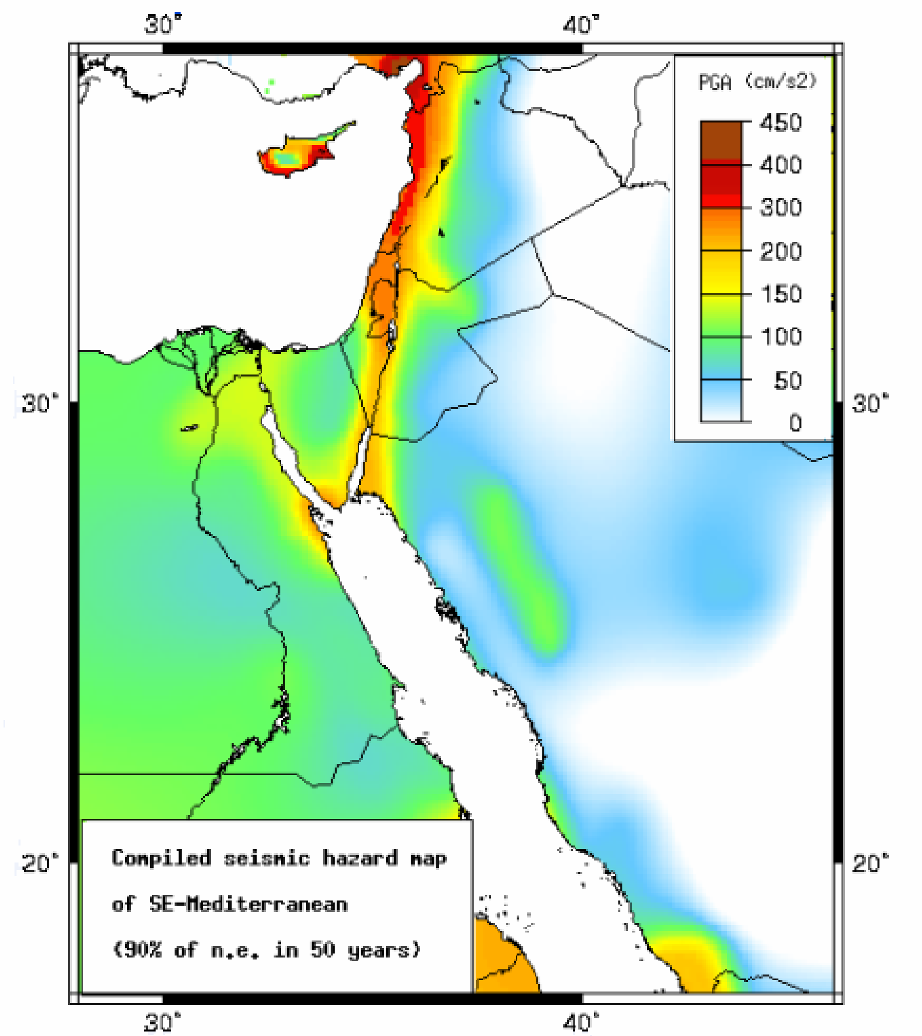


Figure 5.6: Peak Ground Acceleration map expected at 10% probability of exceedence in 50 years in Middle East (http://www.seismo.ethz.ch/gshap/relemr/).

By comparing the previous results with results in this study, we notice that there are some differences, which reflects the methods used to analyze the input data and different equations used in addition to the seismic sources taken into consideration in the analysis, and all of these affect on the results. For examples shapira, and Hofstetter, (2007) worked out the PGA for Aqaba region between 0.20 – 0.25 using Boore et al (1997) attenuation equation for 10% probability of exceedence for an exposure time of 50 years (see figure 5.7), and Jaradat, et al., (2008), worked out the PGA in northern part of Aqaba between 0.16 0.20 using Boore et al (1994) attenuation equation for 10% probability of exceedence for an exposure time of 50 years (see figure 5.8).

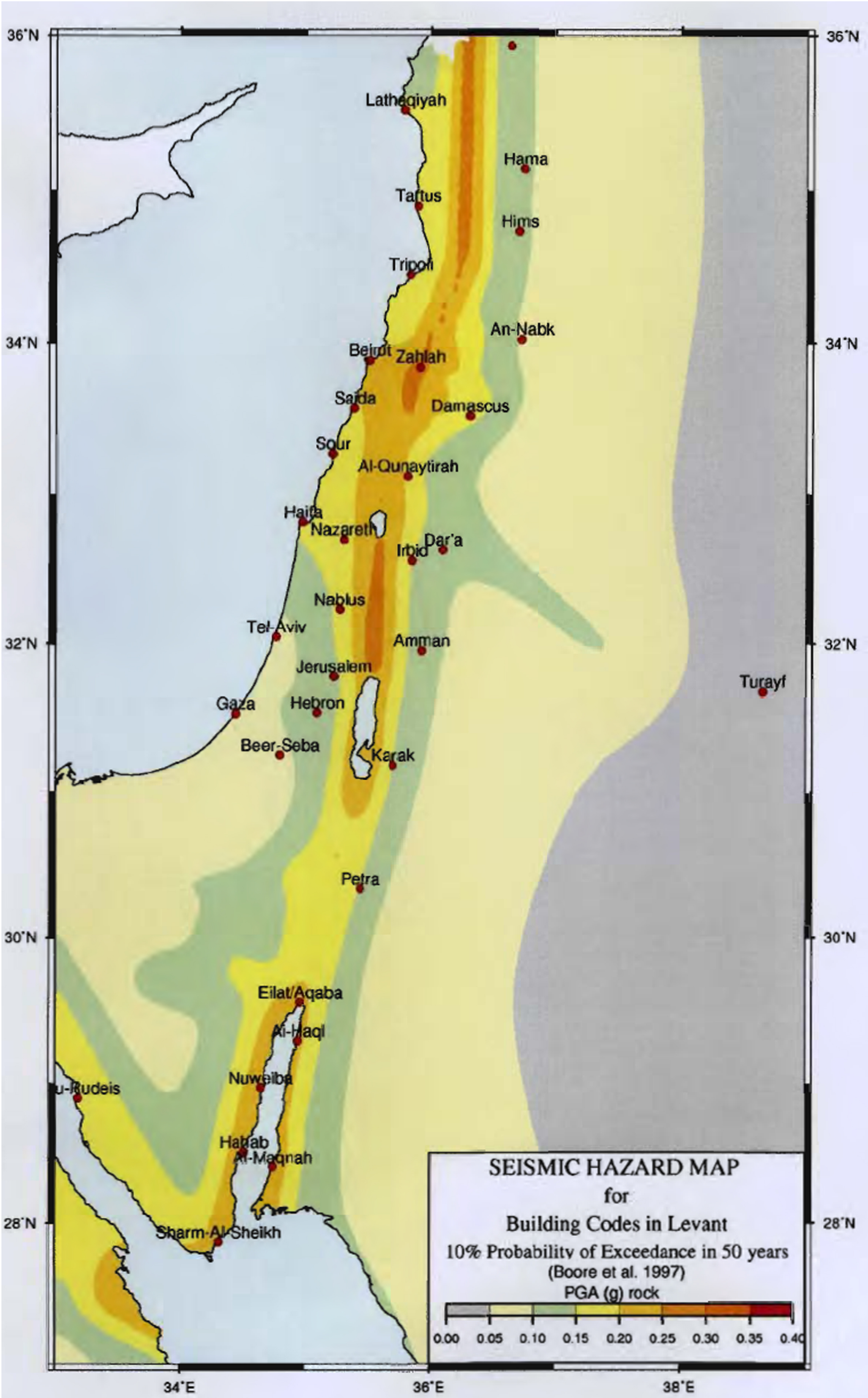


Figure 5.7: Seismic hazard map for Levant region using Boore et al (1997) attenuation equation for 10% probability of exceedence in exposure time of 50 years (Shapira and Hofstetter, 2007).

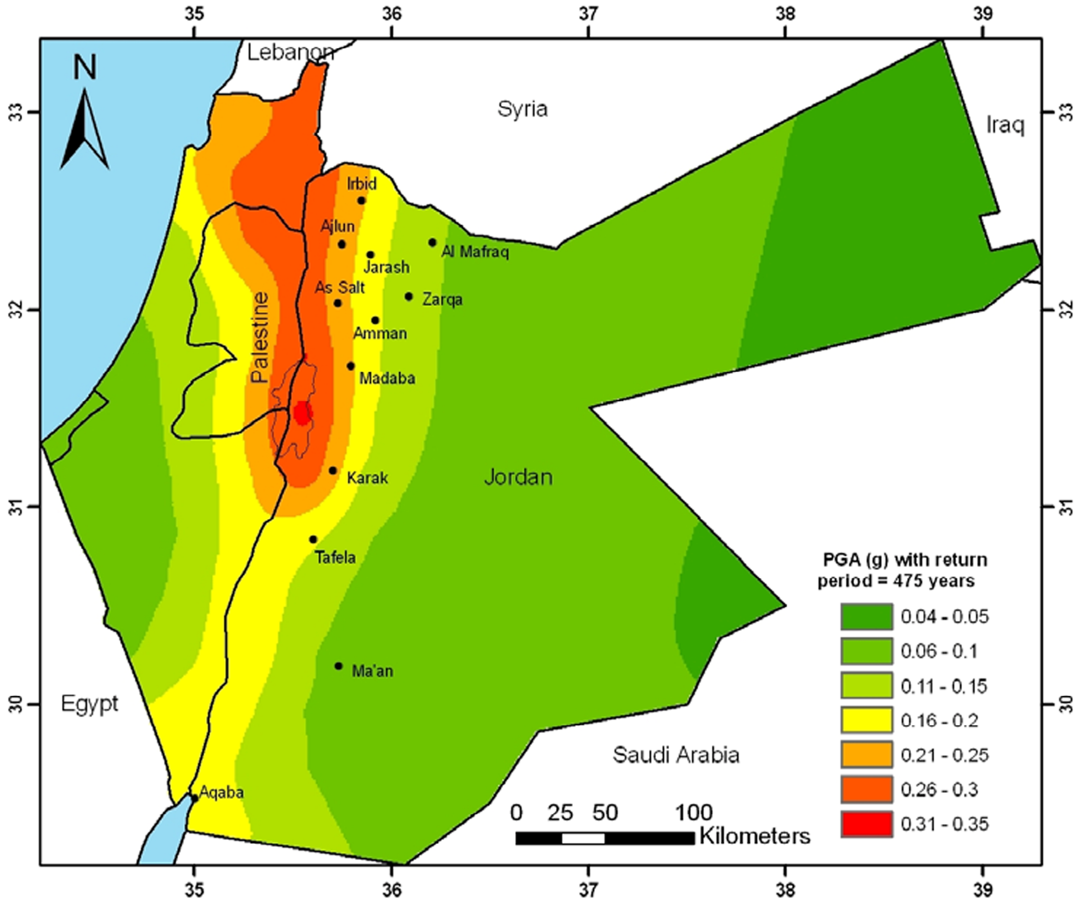


Figure 5.8: Seismic hazard map for Jordan using Boore et al (1994) attenuation equation for 10% probability of exceedence for an exposure time of 50 years (Jaradat, et al., 2008).

However the upper mentioned figures are almost compatible, whether using lower or higher values should be decided and adopted depending on the particular sensitivity of the concerned structure and very local conditions for particularly sensitive projects, a suitable security factor must even be added to the higher PGA values.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIOND

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

- An updated earthquake catalogue is compiled and includes historical and instrumental earthquakes which occurred in Jordan and surrounding area for the period 1-2011 A.D this catalog was used for the seismic hazard assessment in the study area.

- The instrumentally recorded earthquakes are complete in magnitude ≥ 4. Earthquakes with magnitudes less than 3 were not considered in the seismic hazard assessment because of the completeness of the data.

- Reliable location of local earthquakes is a function of data quality and suitable quantity, good coverage of the network stations, and the velocity model used as well as an adapted location algorithm or strategy.

- Three crustal models were tested to relocate all the events which were reported by the available routine monitoring organizations in the area JSO, SNSN, and NIRAG stations, the El-Isa et al. (1986) model is appropriate for the area. This model has shown the least RMS Values associated with the relocation of the selected set of events associated with the Gulf of Aqaba events.

- Wadati diagrams were used to obtain VP/VS values for individual events, and the average values for this ratio is 1.78.

- By applying the methodology developed by Abou Karaki, 1987, 1993 for testing the efficiency of the seismological stations, it is noticed that the stations are suitable for relocation process except 3 stations which were excluded.

- The hypocenter locations for the selected earthquakes were carried out using Seisan program, and the results showed the events to be located on the eastern side of the Gulf.

Results are in agreement with previous results concerning the relocation of the first Gulf of Aqaba swarm of 1983. (Abou Karaki ,1987, Abou Karaki et al, 1993).

-There are small shifts between the new location of the epicenters and the previous results.

-The Seismic hazard assessment in the Gulf of Aqaba is an important step to reduce the risk from earthquakes and property damage. The probabilistic seismic hazard method is used to assess the seismic hazard in this study.

-Seven seismotectonic sources are determined for the seismic hazard assessment in the Gulf of Aqaba, and based on the Jordanian seismic catalogue that includes historical and instrumental records, seismic parameters characterizing the magnitude frequency relationship; activity rate of earthquakes and the maximum magnitude were assigned to each of the seismic sources.

-Appropriate attenuation equations were chosen to relate the expected ground motion at Gulf of Aqaba with the magnitude and distance of the earthquake

-Seismic hazard iso-contouring maps of peak ground acceleration are produced with 10% exceedence of 50 years and these maps are carried out using EZ-FRISK program. These maps show that the highest value corresponds to the northern and central part of the Gulf of Aqaba.

6.2 RECOMENDATIONS

- It is strongly recommended to perform regular updating of the seismic hazard assessment as soon as more data or new attenuation equations taking into consideration the site effects such as the soil distribution, topography, become available.

-Given the particular location of the Gulf as a plate boundary and a political boundary between several states it is highly recommended to enhance the level of cooperation between the seismicity monitoring organizations. There is a need for frequent calibration and possible homogenization of the procedures, material and processes used at least at the Arab level.

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APPENDICES

APPENDICES

Appendix 1.1: The main shock earthquakes used to assess the seismic hazard in Gulf of Aqaba region for the time period (1 – 2010 A.D).

Date	O.T	Lat	Lon	Depth (km)	ML	Ms	Mw	Source code (ML)
03/29/1903	22:03:00	32.200	35.400		5.5	5.4	5.7	BEM
03/29/1903	23:05:00	32.200	35.400		5.1	4.9	5.4	BEM
04/21/1921	8:00:00	33.000	35.500	10.0	4.0	3.8	4.6	BEM
02/27/1923	18:15:00	32.700	35.410	10.0	4.3	4.1	4.8	BEM
02/27/1924	20:04:00	32.710	36.200	10.0	5.1	4.9	5.4	ABK
09/13/1924	21:46:44	30.800	35.500	10.0	4.9	4.7	5.2	ABK
03/16/1925	6:30:00	33.410	36.200	10.0	4.0	3.8	4.6	ABK
05/02/1927	6:20:24	32.500	31.000	33.0	4.6	4.4	5.0	ETA
07/11/1927	13:03:55	32.000	35.500	10.0	6.3	6.2	6.2	ABK
07/17/1927	8:06:00	32.000	35.500	10.0	4.5	4.3	5.0	BEM
09/24/1927	0:28:14	30.400	35.100	10.0	5.0	4.8	5.3	BEM
01/18/1928	5:55:13	32.000	35.500	10.0	4.2	4.0	4.8	BEM
02/03/1928	0:00:00	32.000	35.800	10.0	4.0	3.8	4.6	BEM
02/22/1928	17:50:55	32.000	35.500	10.0	5.0	4.8	5.3	BEM
08/05/1928	3:42:00	32.500	35.600	10.0	4.4	4.2	4.9	BEM
09/13/1928	0:00:00	30.800	35.500	10.0	4.7	4.5	5.1	BEM
11/04/1928	3:34:37	32.000	35.500	10.0	4.2	4.0	4.8	BEM
03/24/1929	12:11:00	32.000	35.500	10.0	4.0	3.8	4.6	IPR
05/21/1930	10:45:00	32.000	35.500	10.0	4.3	4.1	4.8	BEM
10/12/1937	9:56:00	31.500	35.510	10.0	4.2	4.0	4.8	BEM
01/27/1940	5:33:00	32.800	35.100	10.0	4.4	4.2	4.9	BEM
09/02/1940	10:32:00	31.300	35.600	10.0	4.5	4.3	5.0	BEM
09/10/1943	4:52:00	32.600	35.410	10.0	4.7	4.5	5.1	BEM
10/07/1944	10:30:00	32.700	35.500	10.0	4.3	4.1	4.8	BEM
03/19/1945	19:20:00	32.760	35.510	10.0	4.0	3.8	4.6	BEM
09/15/1947	0:40:00	33.010	35.510	10.0	4.0	3.8	4.6	BEM
01/03/1949	19:05:00	32.200	34.200	10.0	4.0	3.8	4.6	BEM
03/01/1950	21:30:00	33.010	35.510	10.0	4.0	3.8	4.6	BEM
01/30/1951	23:07:00	32.400	33.400	10.0	5.7	5.6	5.8	ABK
12/28/1952	2:43:00	32.800	35.400	10.0	4.2	4.0	4.8	BEM
09/13/1954	21:46:00	31.000	35.400	10.0	5.0	4.8	5.3	BEM
03/16/1956	19:32:00	33.350	35.500	10.0	5,5	5.4	5.7	ABK
03/16/1956	19:43:28	33.300	35.500	10.0	6.0	5.9	6.0	ABK
12/18/1956	17:53:00	31.610	35.500	10.0	5.5	5.4	5.7	HAS
11/03/1957	9:56:00	32.500	35.500	10.0	4.5	4.3	5.0	BEM
02/14/1958	23:59:00	31.300	35.600	10.0	4.2	4.0	4.8	BEM
04/10/1959	13:22:00	33.410	35.600	10.0	4.0	3.8	4.6	BEM
05/02/1965	11:52:00	33.400	35.500	10.0	4.3	4.1	4.8	BEM
04/09/1968	13:16:00	32.700	35.600	10.0	4.0	3.8	4.6	BEM
01/02/1969	9:10:00	30.490	35.000	10.0	4.0	3.8	4.6	IPR
01/02/1969	16:21:00	30.500	35.000	10.0	4.0	3.8	4.6	IPR
10/08/1970	2:45:00	31.700	35.300	10.0	4.6	4.4	5.0	BEM
11/08/1971	17:55:00	33.310	35.500	10.0	4.2	4.0	4.8	BEM

09/02/1973	4:01:00	32.810	35.300	10.0	4.2	4.0	4.8	ABK
09/06/1974	5:17:00	29.910	35.500	10.0	4.3	4.1	4.8	IPR
08/17/1977	19:15:00	32.100	35.300	10.0	4.3	4.1	4.8	IPR
08/08/1978	22:06:00	32.810	35.320	10.0	4.0	3.8	4.6	IPR
04/23/1979	13:01:00	31.160	35.500	10.0	5.0	4.8	5.3	IPR
08/14/1979	17:52:00	33.590	34.560	10.0	4.0	3.8	4.6	IPR
11/15/1979	20:04:00	33.560	34.620	10.0	4.0	3.8	4.6	IPR
11/24/1981	9:37:03	33.070	35.650	9.0	4.3	4.1	4.8	IPR
01/21/1983	13:17:32	29.230	34.780	13.0	4.4	4.2	4.9	IPR
01/25/1983	15:59:43	29.030	35.000	21.0	4.4	4.2	4.9	IPR
02/03/1983	23:30:24	29.500	34.870	1.0	5.1	4.9	5.4	IPR
03/19/1983	6:07:40	29.310	34.840	1.0	4.0	3.8	4.6	IPR
03/19/1983	8:49:13	29.610	35.190	1.0	4.1	3.9	4.7	IPR
06/12/1983	12:00:13	28.890	32.960	27.0	5.2	5.0	5.4	IPR
07/19/1983	23:38:58	29.070	34.650	2.0	4.1	3.9	4.7	IPR
10/30/1983	5:35:46	28.720	33.110	27.0	4.2	4.0	4.8	IPR
03/29/1984	21:36:10	30.200	32.190	2.0	4.8	4.6	5.2	ETA
04/06/1984	18:30:56	30.380	33.910	9.0	4.6	4.4	5.0	IPR
04/07/1984	9:20:26	33.750	32.510	27.0	4.4	4.2	4.9	IPR
04/18/1984	20:20:23	28.720	33.220	27.0	4.1	3.9	4.7	JSO
08/24/1984	6:02:25	32.660	35.180	18.0	5.1	4.9	5.4	IPR
10/18/1984	7:19:16	33.160	35.610	3.0	4.3	4.1	4.8	IPR
11/05/1984	1:15:25	32.130	35.370	1.0	4.2	4.0	4.8	IPR
12/21/1984	3:17:47	29.430	32.410	5.0	4.0	3.8	4.6	IPR
01/25/1985	6:08:38	31.920	35.59	15.0	4.9	4.7	5.2	JSO
12/31/1985	19:42:39	29.050	34.990	5.0	5.1	4.9	5.4	IPR
08/07/1986	19:46:53	29.180	34.910	9.0	4.4	4.2	4.9	IPR
08/07/1986	19:52:21	29.200	34.860	8.0	4.1	3.9	4.7	IPR
01/02/1987	10:14:47	30.330	32.300	15.0	4.1	3.9	4.7	JSO
04/27/1987	20:41:47	31.260	35.490	9.0	4.2	4.0	4.8	JSO
10/18/1987	1:05:41	29.510	35.060	10.0	4.5	4.3	5.0	JSO
10/23/1987	16:32:35	31.190	35.340	7.0	4.1	3.9	4.7	JSO
12/14/1987	21:51:05	30.640	31.930	5.0	4.1	3.9	4.7	JSO
01/30/1988	3:00:00	32.200	35.500	12.0	4.1	3.9	4.7	JSO
11/29/1988	17:06:57	28.270	33.540	20.0	4.0	3.8	4.6	JSO
03/31/1989	0:44:14	31.860	37.520	33.0	5.2	5.0	5.4	JSO
09/09/1989	5:16:50	28.570	34.820	9.0	4.1	3.9	4.7	JSO
04/20/1990	14:51:31	28.950	34.790	5.0	4.2	4.0	4.8	JSO
04/26/1990	2:12:47	29.050	34.830	3.0	4.0	3.8	4.6	JSO
09/13/1990	22:10:09	27.010	35.220	13.0	4.7	4.5	5.1	JSO
01/06/1991	21:07:25	31.600	35.500	24.0	4.8	4.6	5.2	JSO
05/15/1991	16:04:12	28.830	34.730	3.0	4.1	3.9	4.7	JSO
05/16/1991	17:28:48	28.910	34.760	5.0	4.1	3.9	4.7	JSO
09/05/1991	22:29:49	28.080	34.380	25.0	4.1	3.9	4.7	JSO
09/28/1991	0:43:07	31.080	35.500	13.0	4.0	3.8	4.6	JSO
10/05/1991	18:48:26	29.500	32.630	6.0	4.2	4.0	4.8	JSO
11/22/1991	0:25:22	27.830	34.890	6.0	4.0	3.8	4.6	JSO
02/03/1992	21:15:16	27.540	34.690	17.0	4.0	3.8	4.6	JSO
09/03/1992	17:09:25	27.680	34.780	9.0	4.4	4.2	4.9	JSO
09/25/1992	22:02:58	27.540	34.100	14.0	4.4	4.2	4.9	JSO
09/27/1992	19:04:28	27.390	34.820	10.0	4.4	4.2	4.9	JSO

10/07/1992	21:34:50	27.740	34.720	17.0	4.1	3.9	4.7	JSO
07/19/1993	8:53:52	27.530	34.380	16.0	4.2	4.0	4.8	JSO
08/03/1993	12:43:08	28.450	34.820	13.0	5.8	5.7	5.9	JSO
09/05/1993	13:15:19	28.390	34.820	9.0	4.1	3.9	4.7	JSO
09/06/1993	6:51:28	28.710	34.840	14.0	4.4	4.2	4.9	JSO
09/07/1993	1:14:29	28.280	34.760	7.0	4.3	4.1	4.8	JSO
09/09/1993	23:42:45	28.450	34.610	7.0	4.1	3.9	4.7	JSO
09/10/1993	19:48:41	28.350	34.670	10.0	4.2	4.0	4.8	JSO
09/12/1993	23:15:45	28.080	34.650	7.0	4.5	4.3	5.0	JSO
09/13/1993	0:02:55	28.270	34.660	7.0	4.5	4.3	5.0	JSO
09/20/1993	20:17:53	27.900	34.880	16.0	4.6	4.4	5.0	JSO
09/25/1993	0:52:50	28.240	34.630	13.0	4.1	3.9	4.7	JSO
10/03/1993	17:48:56	28.310	34.920	9.0	4.3	4.1	4.8	JSO
10/10/1993	11:17:00	28.350	34.750	16.0	4.2	4.0	4.8	JSO
10/16/1993	11:38:26	28.510	34.910	14.0	4.2	4.0	4.8	JSO
10/17/1993	20:58:10	28.820	34.770	9.0	4.1	3.9	4.7	JSO
10/18/1993	20:51:06	28.050	34.890	14.0	4.9	4.7	5.2	JSO
10/20/1993	22:42:08	28.160	34.870	16.0	4.1	3.9	4.7	JSO
10/21/1993	0:34:56	28.060	34.810	9.0	4.8	4.6	5.2	JSO
10/24/1993	0:50:27	28.850	34.540	9.0	4.0	3.8	4.6	JSO
11/01/1993	7:48:45	28.800	34.750	5.0	4.2	4.0	4.8	JSO
11/03/1993	18:39:25	27.980	34.880	16.0	5.3	5.1	5.5	JSO
11/07/1993	23:10:13	28.260	34.810	16.0	4.2	4.0	4.8	JSO
11/08/1993	1:05:55	28.040	34.800	9.0	5.0	4.8	5.3	JSO
11/08/1993	22:56:14	28.700	34.680	6.0	4.0	3.8	4.6	JSO
11/20/1993	11:35:58	28.720	34.690	3.0	4.2	4.0	4.8	JSO
12/04/1993	23:34:15	28.770	34.910	10.0	4.9	4.7	5.2	JSO
12/21/1993	3:13:11	28.860	34.550	5.0	4.0	3.8	4.6	JSO
12/31/1993	10:26:15	28.620	34.730	2.0	4.3	4.1	4.8	JSO
01/01/1994	3:10:41	28.950	34.760	6.0	4.4	4.2	4.9	JSO
01/03/1994	10:49:32	28.700	34.810	5.0	4.5	4.3	5.0	JSO
01/31/1994	21:27:56	27.760	34.530	14.0	4.4	4.2	4.9	JSO
02/10/1994	21:26:30	29.010	34.810	5.0	4.0	3.8	4.6	JSO
02/17/1994	23:13:31	28.700	34.830	5.0	4.5	4.3	5.0	JSO
04/06/1994	21:18:31	28.510	34.850	14.0	4.8	4.6	5.2	JSO
04/28/1994	8:06:55	28.890	34.590	3.0	4.0	3.8	4.6	JSO
07/03/1994	14:26:41	28.770	34.670	1.0	4.5	4.3	5.0	JSO
07/04/1994	1:06:06	28.630	34.680	2.0	4.4	4.2	4.9	JSO
07/05/1994	10:01:00	28.700	34.650	2.0	4.5	4.3	5.0	JSO
08/19/1994	1:30:23	28.120	34.510	5.0	4.3	4.1	4.8	JSO
09/16/1994	3:18:57	32.050	35.500	18.0	4.1	3.9	4.7	JSO
05/14/1995	4:04:45	28.230	34.990	10.0	4.0	3.8	4.6	JSO
05/14/1995	7:02:53	27.800	34.330	2.0	4.2	4.0	4.8	JSO
06/09/1995	23:30:37	28.690	34.610	5.0	4.2	4.0	4.8	JSO
11/22/1995	4:15:12	28.760	34.680	14.0	6.2	6.3	6.3	JSO
02/02/1999	18:01:28	28.830	34.670	1.0	4.0	3.8	4.6	JSO
06/13/1999	4:20:11	28.280	34.750	11.0	4.9	4.7	5.2	JSO
06/13/1999	6:22:47	28.120	34.640	8.0	4.2	4.0	4.8	JSO
06/17/1999	14:20:21	27.990	34.660	10.0	4.3	4.1	4.8	JSO
06/17/1999	14:23:04	27.900	34.540	25.0	4.3	4.1	4.8	JSO
06/17/1999	15:49:31	28.160	34.860	6.0	4.0	3.8	4.6	JSO

10/05/1999	5:44:36	28.910	34.900	14.0	4.8	4.6	5.2	JSO
10/28/1999	15:39:15	30.400	34.980	9.0	4.6	4.4	5.0	JSO
12/03/1999	14:07:09	29.300	35.000	16.0	4.3	4.1	4.8	JSO
12/08/1999	3:35:48	29.310	34.800	5.0	4.0	3.8	4.6	JSO
12/19/1999	8:42:49	29.700	34.960	17.0	4.1	3.9	4.7	JSO
01/17/2000	8:24:39	28.750	34.790	3.0	4.0	3.8	4.6	JSO
03/08/2000	14:22:17	28.870	34.890	15.0	4.9	4.7	5.2	JSO
04/06/2000	6:36:37	28.820	34.920	3.0	4.7	4.5	5.1	JSO
06/15/2000	21:31:17	31.360	33.670	31.0	4.7	4.5	5.1	JSO
06/25/2000	19:18:34	28.010	32.580	10.0	4.7	4.5	5.1	JSO
07/22/2000	10:14:41	29.030	34.510	15.0	4.3	4.1	4.8	JSO
07/30/2000	22:22:52	27.470	34.350	31.0	4.2	4.0	4.8	JSO
08/27/2000	3:39:52	28.850	34.830	8.0	4.3	4.1	4.8	JSO
09/17/2000	10:54:22	29.100	34.830	11.0	4.0	3.8	4.6	JSO
09/29/2000	10:51:52	27.920	34.250	74.0	4.2	4.0	4.8	JSO
09/30/2000	21:41:47	28.450	33.600	3.0	4.4	4.2	4.9	JSO
10/08/2000	2:58:50	29.370	35.190	15.0	4.1	3.9	4.7	JSO
11/03/2000	21:14:49	28.980	32.810	15.0	5.2	5.0	5.4	JSO
11/20/2000	5:35:59	27.510	34.300	31.0	4.2	4.0	4.8	JSO
12/25/2000	1:57:54	28.520	34.570	19.0	4.5	4.3	5.0	JSO
02/07/2001	3:38:57	29.330	34.980	16.0	4.3	4.1	4.8	JSO
04/29/2001	10:59:26	29.190	34.800	1.0	4.0	3.8	4.6	JSO
08/04/2001	15:30:05	28.900	34.870	1.0	4.0	3.8	4.6	JSO
10/08/2001	11:24:37	30.460	35.300	17.0	4.0	3.8	4.6	JSO
12/29/2001	12:19:34	28.460	34.670	1.0	4.5	4.3	5.0	JSO
02/25/2002	7:25:01	27.520	34.830	15.0	4.5	4.3	5.0	JSO
03/11/2002	12:04:05	28.920	34.860	8.0	4.0	3.8	4.6	JSO
11/11/2002	16:45:02	28.390	34.640	1.0	4.0	3.8	4.6	JSO
04/18/2003	5:44:26	28.850	34.750	3.0	4.3	4.1	4.8	JSO
07/12/2003	9:22:10	28.400	33.560	19.0	4.0	3.8	4.6	JSO
07/23/2003	16:36:42	28.890	34.790	12.0	4.3	4.1	4.8	JSO
12/25/2003	8:08:15	28.530	34.730	4.0	4.0	3.8	4.6	JSO
02/11/2004	8:14:57	31.690	35.580	22.0	4.9	4.7	5.2	JSO
03/15/2004	23:49:54	31.380	35.560	14.0	4.0	3.8	4.6	JSO
05/01/2004	17:13:47	28.360	34.700	15.0	4.1	3.9	4.7	JSO
07/07/2004	14:35:01	31.970	35.580	19.0	4.6	4.4	5.0	JSO
02/07/2005	10:27:36	31.150	35.500	4.0	4.0	3.8	4.6	JSO
07/07/2005	14:44:34	28.600	34.480	1.0	4.0	3.8	4.6	JSO
10/03/2005	4:03:08	32.040	35.640	23.0	4.2	4.0	4.8	JSO
02/02/2006	9:49:49	27.829	34.621	0.0	4.4	4.2	4.9	JSO
09/09/2006	4:58:10	32.042	35.525	7.9	4.4	4.2	4.9	JSO
09/17/2006	8:22:51	32.035	35.520	6.5	4.2	4.0	4.8	JSO
11/18/2006	2:57:55	32.051	35.509	0.0	4.1	3.9	4.7	JSO
02/09/2007	22:14:08	31.067	35.504	15.0	4.7	4.5	5.1	JSO
11/20/2007	9:18:46	31.692	35.581	9.9	4.3	4.1	4.8	JSO
11/23/2007	22:19:56	31.860	35.005	15.0	4.1	3.9	4.7	JSO
12/02/2007	7:38:14	31.672	35.617	7.5	4.3	4.1	4.8	JSO
02/12/2008	14:19:39	33.281	35.369	2.7	4.0	3.8	4.6	JSO
02/15/2008	10:36:26	32.900	35.618	15.0	5.3	5.1	5.5	JSO
02/15/2008	12:15:16	33.314	35.273	0.0	4.4	4.2	4.9	JSO
02/15/2008	13:26:48	33.476	36.524	34.4	4.1	3.9	4.7	JSO

03/01/2008	**5:47:35**	**33.226**	**35.325**	**0.1**	**4.0**	**3.8**	**4.6**	**JSO**
04/04/2008	**14:05:26**	**29.053**	**34.997**	**15.0**	**4.5**	**4.3**	**5.0**	**JSO**
04/07/2008	**1:33:06**	**32.970**	**34.927**	**2.3**	**4.1**	**3.9**	**4.7**	**JSO**
04/12/2008	**01:30 :12**	**27.646**	**37.040**	**0.0**	**4.1**	**3.9**	**4.7**	**JSO**
06/12/2008	**12:58:14**	**33.241**	**35.414**	**1.6**	**4.0**	**3.8**	**4.6**	**JSO**
06/12/2008	**15:41:01**	**33.529**	**35.235**	**27.7**	**4.3**	**4.1**	**4.8**	**JSO**
04/17/2009	**11:03: 59**	**33.346**	**35.257**	**0.0**	**4.3**	**4.1**	**4.8**	**JSO**
07/10/2009	**18:19:19**	**33.231**	**35.423**	**0.2**	**4.4**	**4.2**	**4.9**	**JSO**
07/15/2010	**11:25:55**	**28.949**	**35.000**	**10**	**4.2**	**4.0**	**4.8**	**JSO**

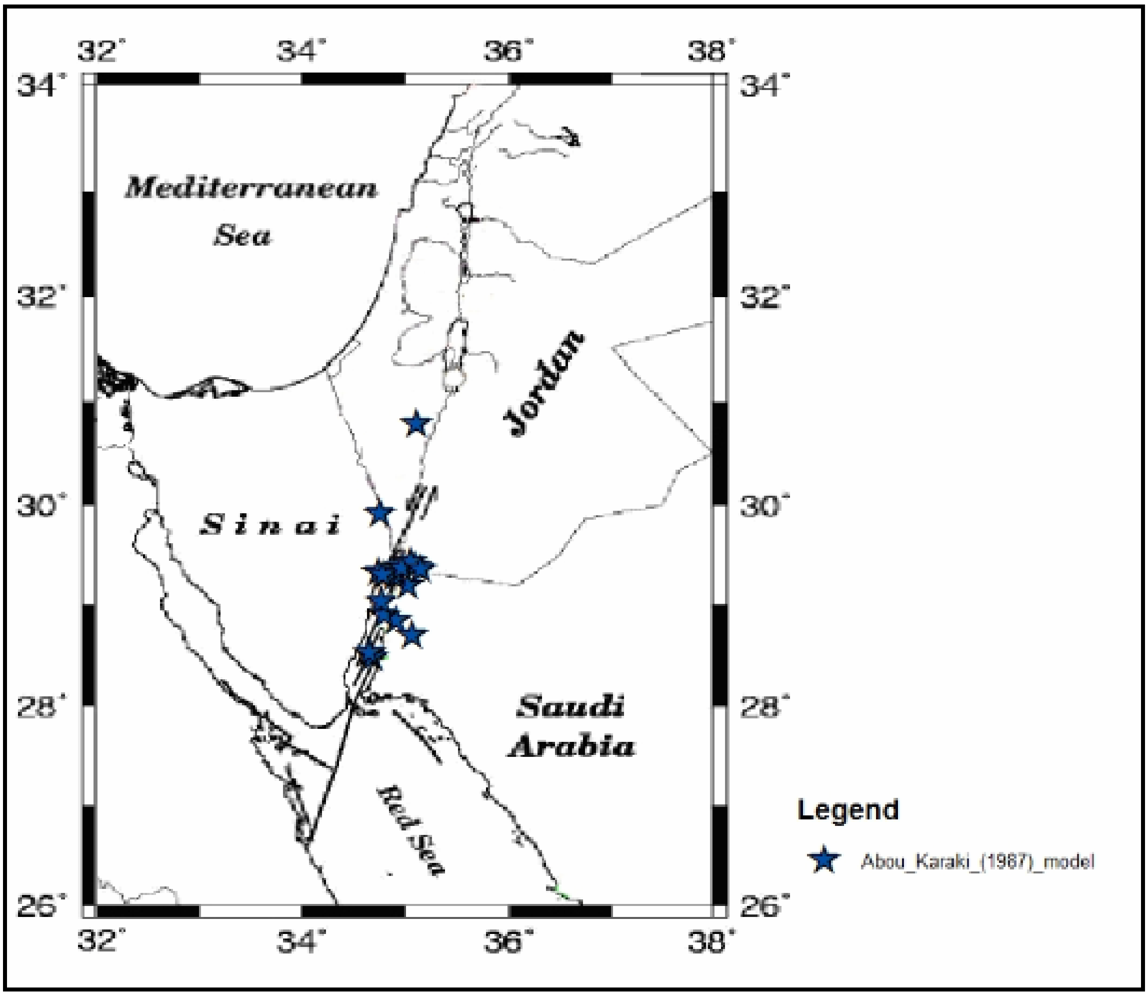
APPENDIX 2

The RMS residuals for earthquake events used for relocation processing. The source of data for the events from Saudi Arabia (SNSN, King Abdulaziz City for Sci. and Tech) and Egypt, National Research Institute of Astronomy and Geophysics (NRIAG) Helwan.

Appendix 2.1: The coordinates of the newly determined hypocenters, and the associated RMS values of the relocation process using Abou Karaki (1987) model.

Date	Time	Lat	Long	RMS	station
09/01/2004	09:54:36	29.177	35.038	0.28	13
10/01/2004	22:28:31	28.472	34.689	0.28	5
16/01/2004	15:18:43	28.515	34.672	0.35	10
21/01/2004	02:42:56	29.878	34.769	0.3	14
24/01/2004	15:51:09	29.352	35.109	0.31	9
26/01/2004	12:25:56	29.404	35.071	0.24	8
29/01/2004	18:47:07	28.82	34.92	0.35	6
09/02/2004	00:42:41	28.889	34.806	0.26	7
10/02/2004	21:10:23	29.262	34.904	0.27	9
10/02/2004	21:27:17	29.298	34.919	0.11	9
10/02/2004	22:55:45	29.295	34.915	0.13	8
11/02/2004	03:54:40	30.755	35.127	0.19	6
11/02/2004	06:47:33	29.303	34.754	0.35	8
11/02/2004	10:45:40	28.679	35.085	0.18	7
12/02/2004	01:04:54	29.269	34.799	0.32	9
15/02/2004	19:52:39	29.339	34.977	0.2	9
25/02/2004	04:38:10	29.324	35.17	0.39	7
25/02/2004	14:53:46	29.015	34.773	0.31	9

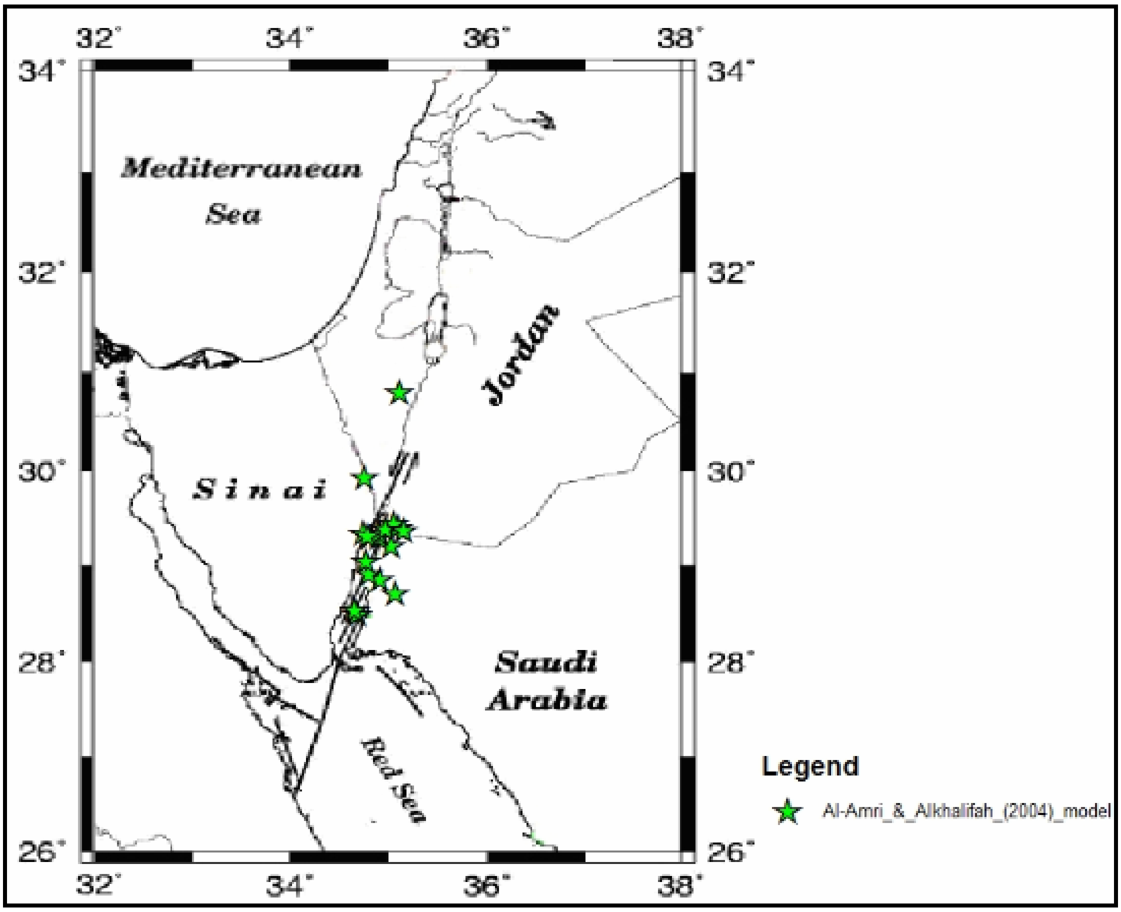
Appendix 2.2: Epicentral distribution of the events listed in appendix 2.1 after relocation process.



Appendix 2.3: The coordinates of the newly determined hypocenters and the associated RMS values of the relocation process using Al-Amri & Alkhalifah (2004) model

Date	Time	Lat	Long	RMS	station
09/01/2004	09:54:36	29.172	34.998	0.23	13
10/01/2004	22:28:31	28.484	34.688	0.4	5
16/01/2004	15:18:43	28.514	34.675	0.33	10
21/01/2004	02:42:56	29.872	34.754	0.47	14
24/01/2004	15:51:09	29.37	35.082	0.42	9
26/01/2004	12:25:56	29.399	35.062	0.45	8
29/01/2004	18:47:07	28.814	34.921	0.49	6
09/02/2004	00:42:41	28.894	34.814	0.34	7
10/02/2004	21:10:23	29.259	34.914	0.34	9
10/02/2004	21:27:17	29.288	34.922	0.18	9
10/02/2004	22:55:45	29.287	34.917	0.22	8
11/02/2004	03:54:40	30.718	35.105	0.2	6
11/02/2004	06:47:33	29.28	34.794	0.31	8
11/02/2004	10:45:40	28.698	35.082	0.23	7
12/02/2004	01:04:54	29.266	34.776	0.36	9
15/02/2004	19:52:39	29.339	34.978	0.15	9
25/02/2004	04:38:10	29.314	35.157	0.3	7
25/02/2004	14:53:46	29.014	34.769	0.28	9

Appendix 2.4: Epicentral distribution of the events listed appendix 2.3 after relocation process.



الوضع الزلزالي- التكتوني وتقييم الأخطار الزلزالية في منطقة خليج العقبة

إعداد
أسماء محمد غنام

المشرف
الأستاذ الدكتور نجيب أبوكركي

مجموعة من الزلازل الواقعة في منطقة خليج العقبة والتي تم جمع البيانات المتعلقة فيها من عدة مصادر وهي البيانات الصادرة من سلطة المصادر الطبيعية, مدينة الملك عبد العزيز للأبحاث, والمعهد الوطني للأبحاث الفلكية والجيوفيزيائية في مصر, تم إعادة تحديد مواقعها بعد الأخذ بعين الاعتبار دراسة أزمان الوصول للأمواج الأولية والثانوية, اختبار كفاءة المحطات المستخدمة في تحديد مواقعها, حساب معدل سرعة وصول الأمواج الأولية إلى سرعة الأمواج الثانوية, واختيار أفضل نموذج سرعات ممثل للمنطقة بالمعنى الإحصائي . تبين من إعادة تحديد مواقع الزلازل التي تمت دراستها أنها موزعة بشكل رئيس على الجانب الشرقي من خليج العقبة.

إن تطوير خرائط الخطر الزلزالي في منطقة خليج العقبة اعتمد الطريقة الاحتمالية وعلى جميع المعلومات عن الزلازل القديمة والمسجلة, المعلومات الجيولوجية والتكتونية وتبعا لذلك قسمت المنطقة إلى 7 أنطقه زلزالية. تم إخراج عدد من الثوابت مثل المعدل السنوي لحدوث الزلازل وأكبر قوة للزلازل و معامل b لكل من الأنطقة الزلزالية.

استخدمت الاحتمالية الكلية لتحديد أن قيم التسارع الأرضي لن تزيد باحتمالية 90% عن قيم تسارع افتراضية خلال أعمار تصميمية مقدارها50 سنة. بينت الخرائط قيماً متوقعة للتسارع الأرضي لمنطقة خليج العقبة وصلت (0.29 g) في الجزء الأوسط من الخليج.